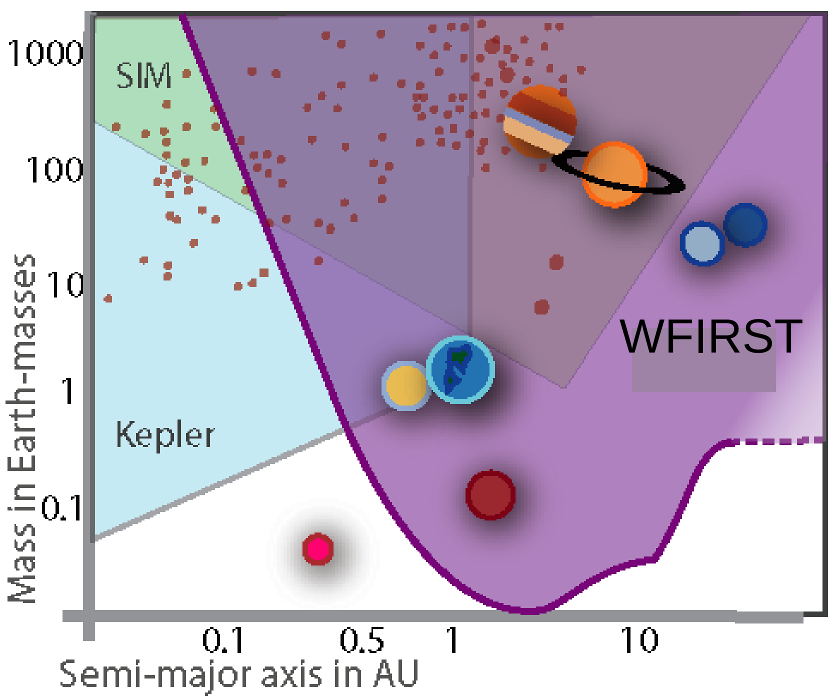
WFIRST
Wide-Field Infra-Red Survey Telescope

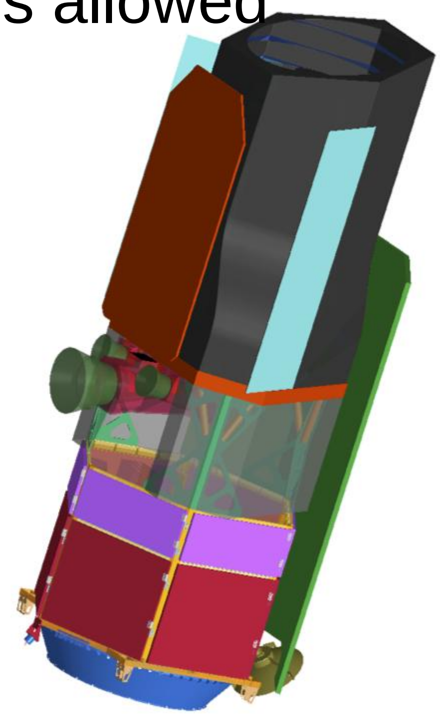
Update

David Bennett

WFIRST SDT member

No unofficial comments by SDT members allowed

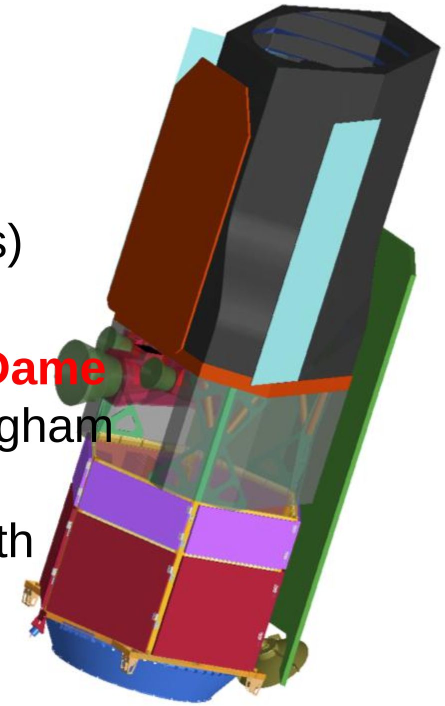




WFIRST

Wide-Field Infra-Red Survey Telescope

SDT



Science Definition Team (SDT) Membership

J. Green, Colorado/CASA   P. Schechter, MIT (Co-Chairs)

R. Bean, Cornell University,

C. Bennett, JHU

R. Brown, STScI

M. Donahue, Michigan State

T. Lauer, NOAO*

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J. Rhodes, JPL*

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A. Tanner, Georgia State Univ.

E. Wright, UCLA

C. Baltay, Yale

D. Bennett, Notre Dame

C. Conselice, Nottingham

S. Gaudi, Ohio State

B. Nichol, Portsmouth

B. Rauscher, GSFC

T. Roellig, Ames

T. Sumi, Osaka Univ.

Y. Wang, Oklahoma

N. Gehrels, GSFC (Ex-Officio)

R. Sambruna, NASA HQ (Ex-Officio)

W. Traub, JPL (Ex-Officio)

*Co-I’s on original μlensing exoplanet + DE proposal: GEST

more info: http://wfirst.gsfc.nasa.gov/

Implementing NWNH Report

- NAS Committee – Burrows & Kennel with Dressler, Elmegreen, Harrison, Hillenbrand, Ritz & Young
- NWNH thought mission timing was important
- 4 options
  - A. WFIRST as recommended – by 2021
  - B. Joint mission with Euclid
    - Including all WFIRST science
    - ESA could lead it
  - C. 20% of Euclid – non-responsive to NWNH
  - D. Nothing – non-responsive to NWNH
- OMB really likes option B
  - But OMB has much less influence over ESA than over NASA….

SDT Reports

- Preliminary report – due June 30, 2011
  - Generate WFIRST mission concept
    - w/ science program from NWNH
  - Basis for 1st cost estimate
  - Basis for negotiations with Euclid
  - Basis for descope comparisons
- Informal Advice for discussions with Euclid
- Final Report – due in 2012
  - More serious attempt at cost reduction
  - More consideration of joint mission, etc.

WFIRST plus or vs. Euclid

- Euclid, PLATO, Solar Orbiter down-selection announced on October 4
- Down-selections made in February, 2012 (?)
  - Interval is needed to make financial arrangements with partners – apparently both European National and outside agencies
- *(Politically incorrect comments about ESA and NASA removed)*
- Top-level NASA and higher officials will likely make the case for joint WFIRST-Euclid mission to higher levels of ESA

WFIRST plus (or vs.) Euclid Options

- If Euclid is selected
  - US as a major partner, but perhaps ESA leads
  - Probably based on Euclid design?
- If Euclid is rejected this round
  - Enters the finals (vs. Echo) for the next M-class spot
    - 1 slot with more competitors
  - Considers joining WFIRST?
- If Euclid is selected but says no to WFIRST merger
  - SDT likely to consider descope options that maximize the science with Euclid going forward

WFIRST & JWST

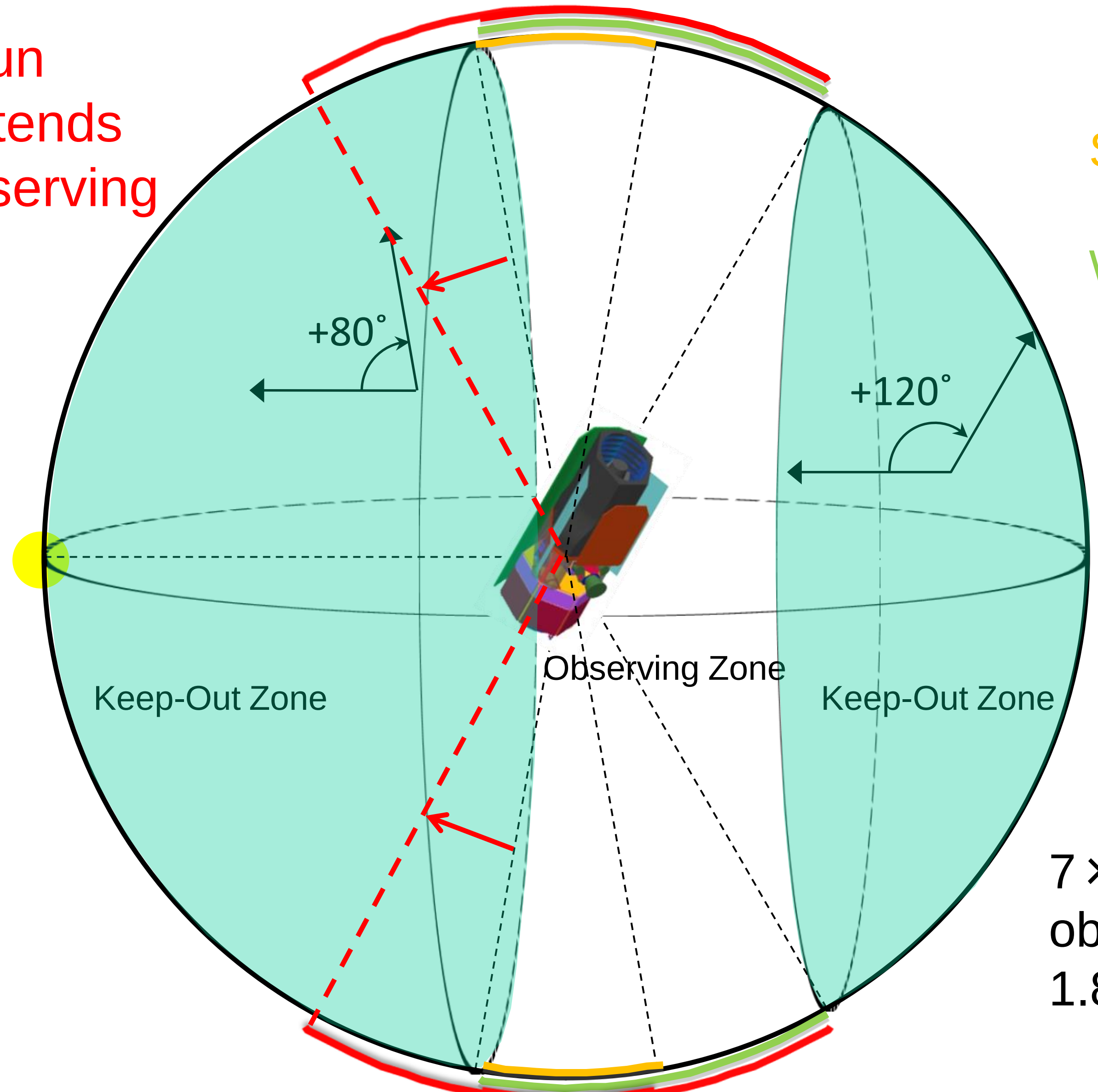
- Science of WFIRST is enhanced by mission overlap with JWST
  - Wide-field IR surveys provide JWST targets
  - WFIRST Supernovae spectra have low S/N
    - WFIRST SNe program could be greatly enhanced if combined with a JWST key project to get spectra of 500 WFIRST Sne
    - small, wide-FOV telescope for imaging – large telescope for spectra
- Of course, coupling requirements for different missions is pretty dangerous

Changes to JDEM-Ω Design

- JDEM-Ω has only 2 50-day observing windows per year to the bulge (near the equinoxes)
  - Due to relatively trivial thermal design and scattered light issues
- 500-days of microlensing observations requires all 10 such observing windows
- This implies no room for the desired Supernova observations
  - They want 25% of the time over 2 years to get good sampling of SNe at high-z

Payload Central Line of Sight Field of Regard

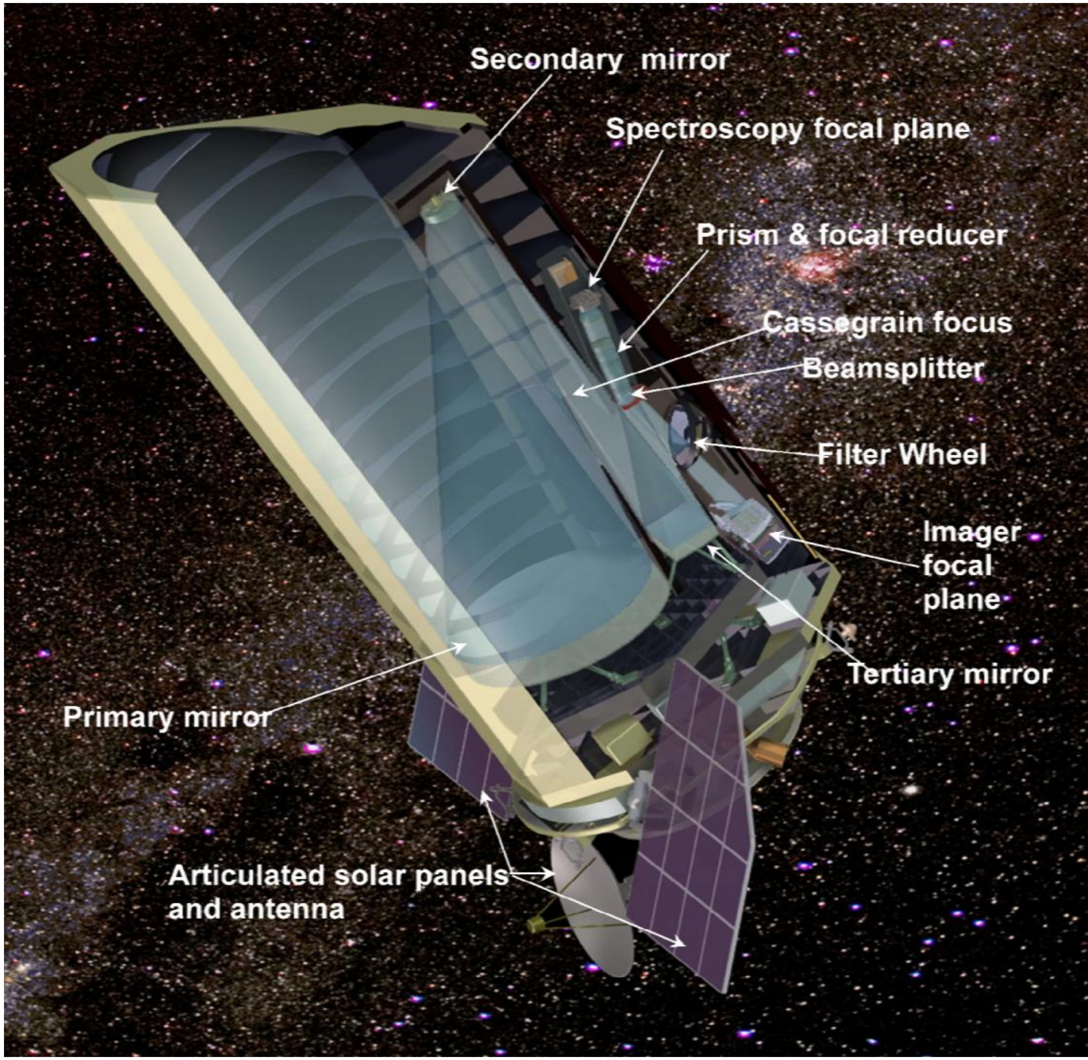
Larger Sun shield extends bulge observing window



7 × 72 day bulge observing periods, 1.8 year SNe run

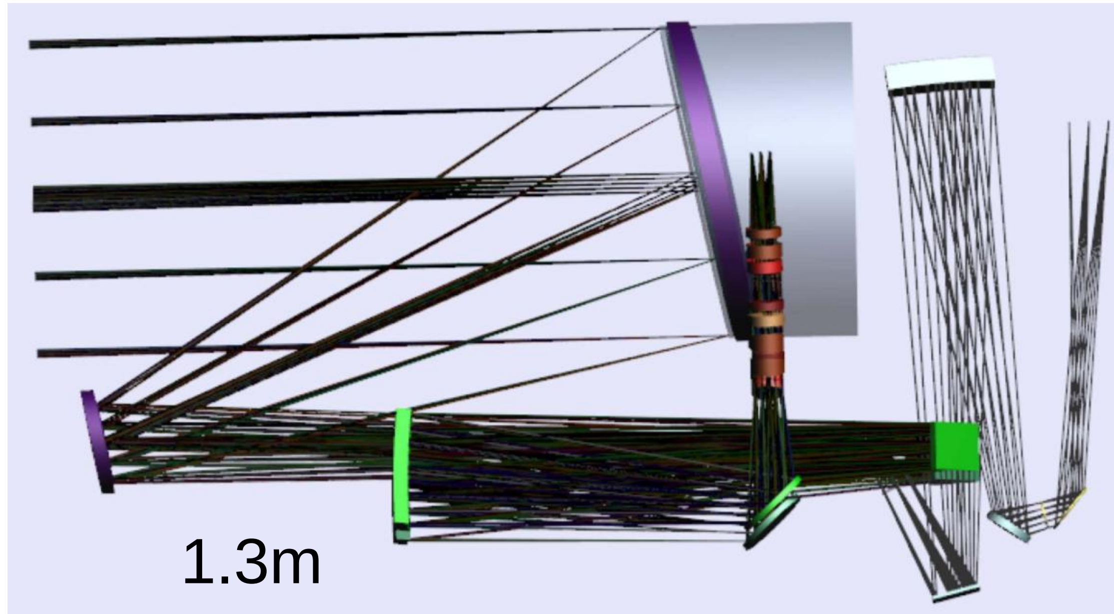
Levi et al. (arXiv.org:1105.0959)

- A better solution
- 270 day bulge observing seasons
- Articulated solar arrays
- Aft sunshield
- Allows exoplanet dominated extended mission, should it be needed (i.e. if HZ proves to be much narrower than current estimates)
- Few constraints on GO observations

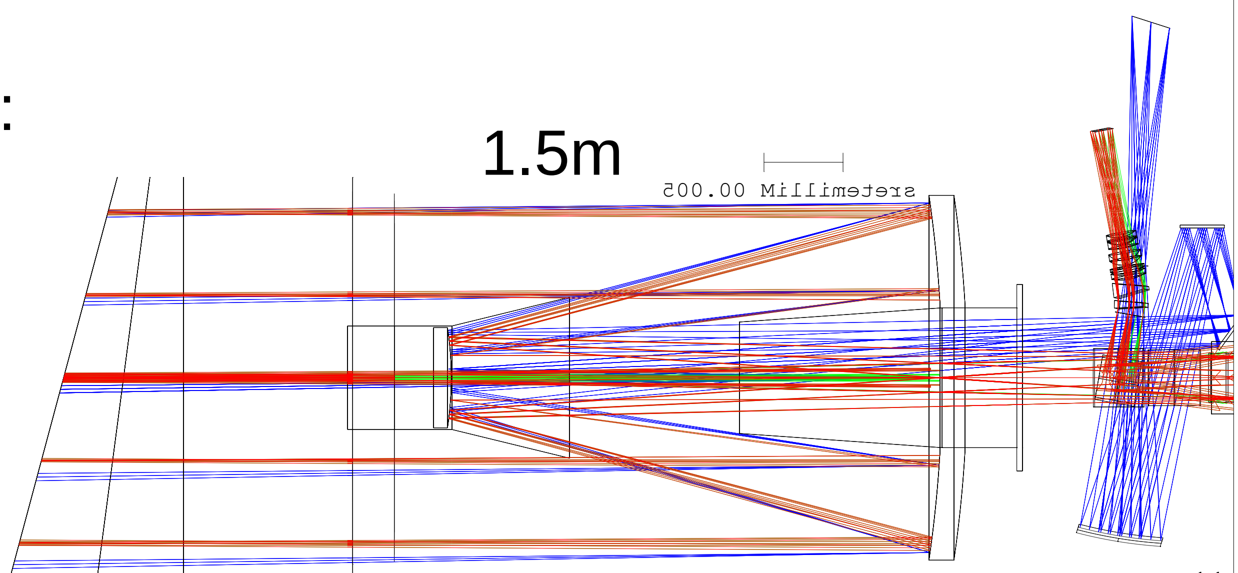


1.5m on-axis -> 1.3m off-axis

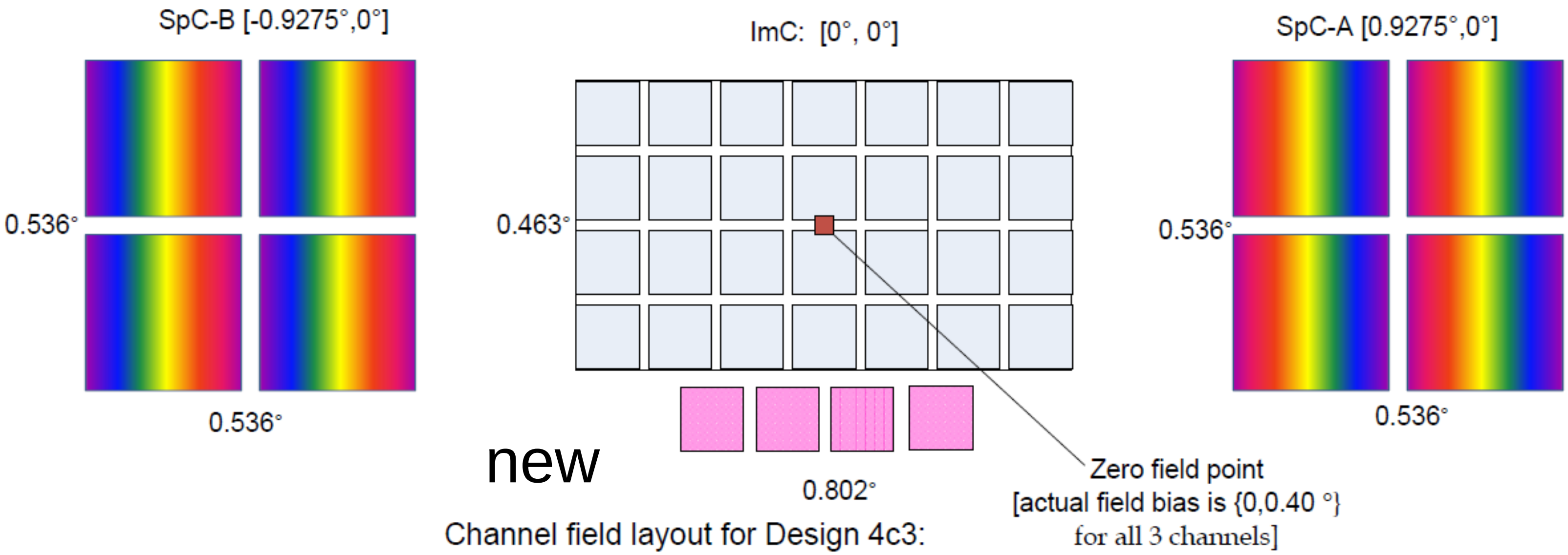
- Unobscured off-axis design has sharper images.
- Many examples (i.e. comercial Earth-observing)
- But slower primary needed



- Unrelated change: telescope mass drops by almost a factor of 2

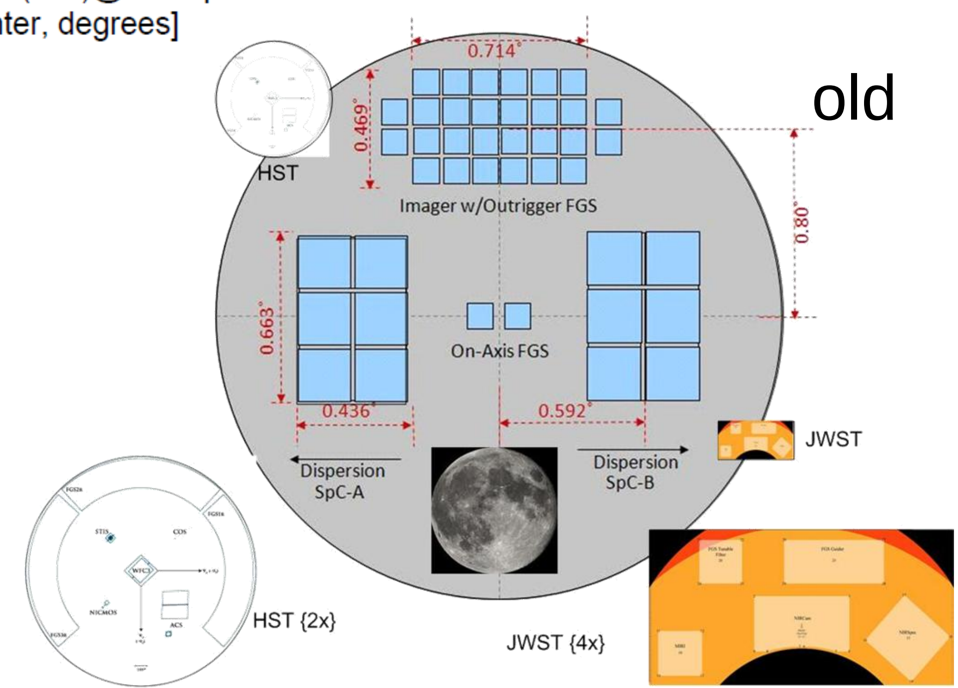


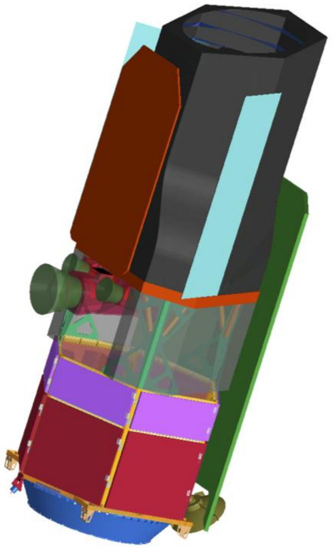
Improved Focal Plane Layout



Channel field layout for Design 4c3:
ImC: 7x4 @ 0.18"/p; SpC 2(2x2)@0.45"/p
[xfield center, yfield center, degrees]

- Imager was 4 × 6 – now 4 × 7
- 4 detectors moved from spectrograph to imager

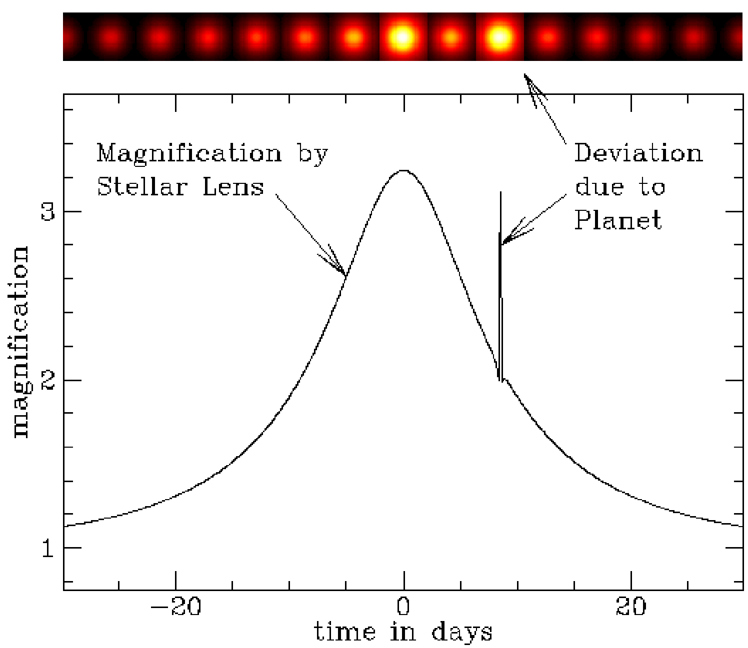


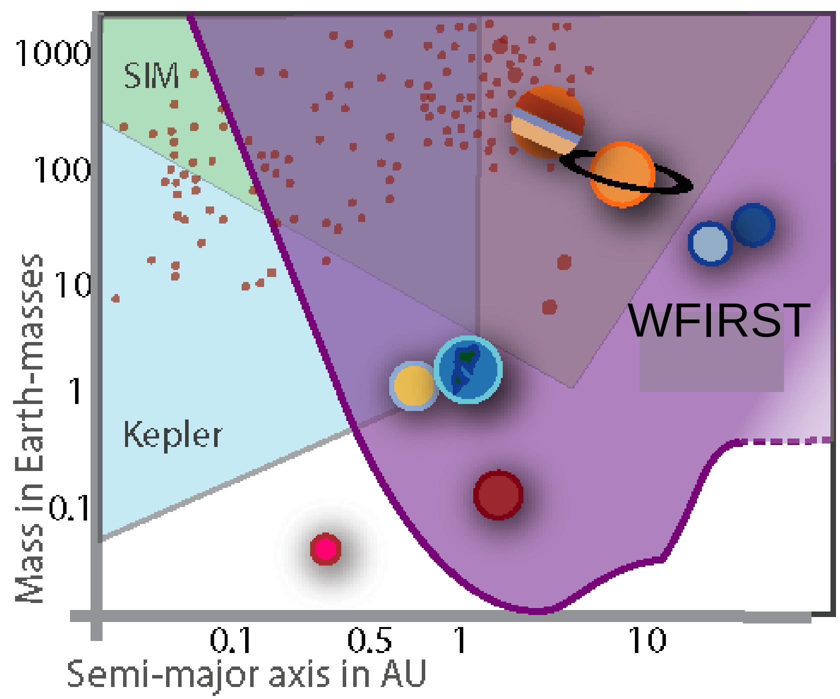


The WFIRST Microlensing Exoplanet Survey:

Figure of Merit

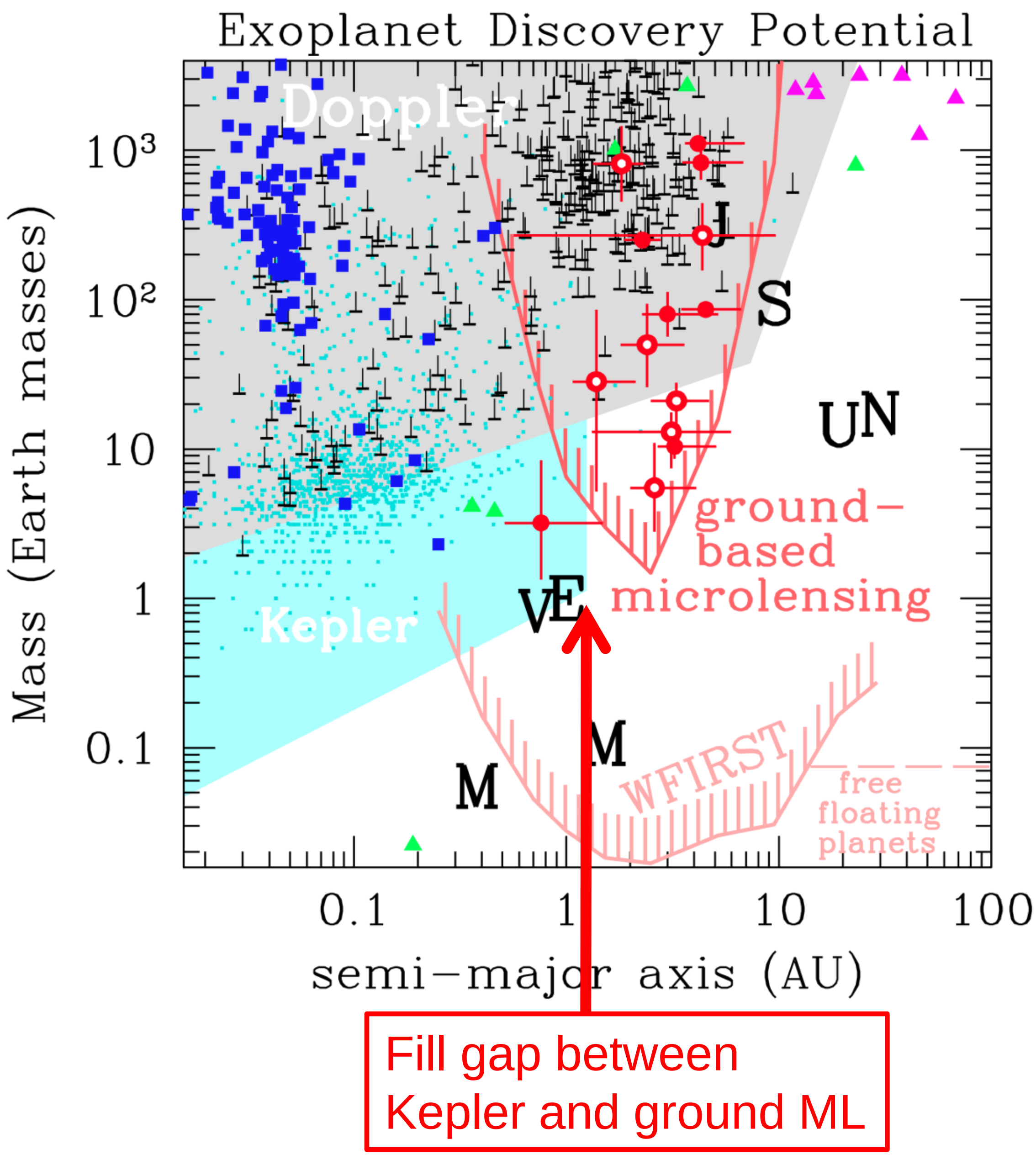
WFIRST
Wide-Field Infra-Red Survey Telescope





Planet Discoveries by Method

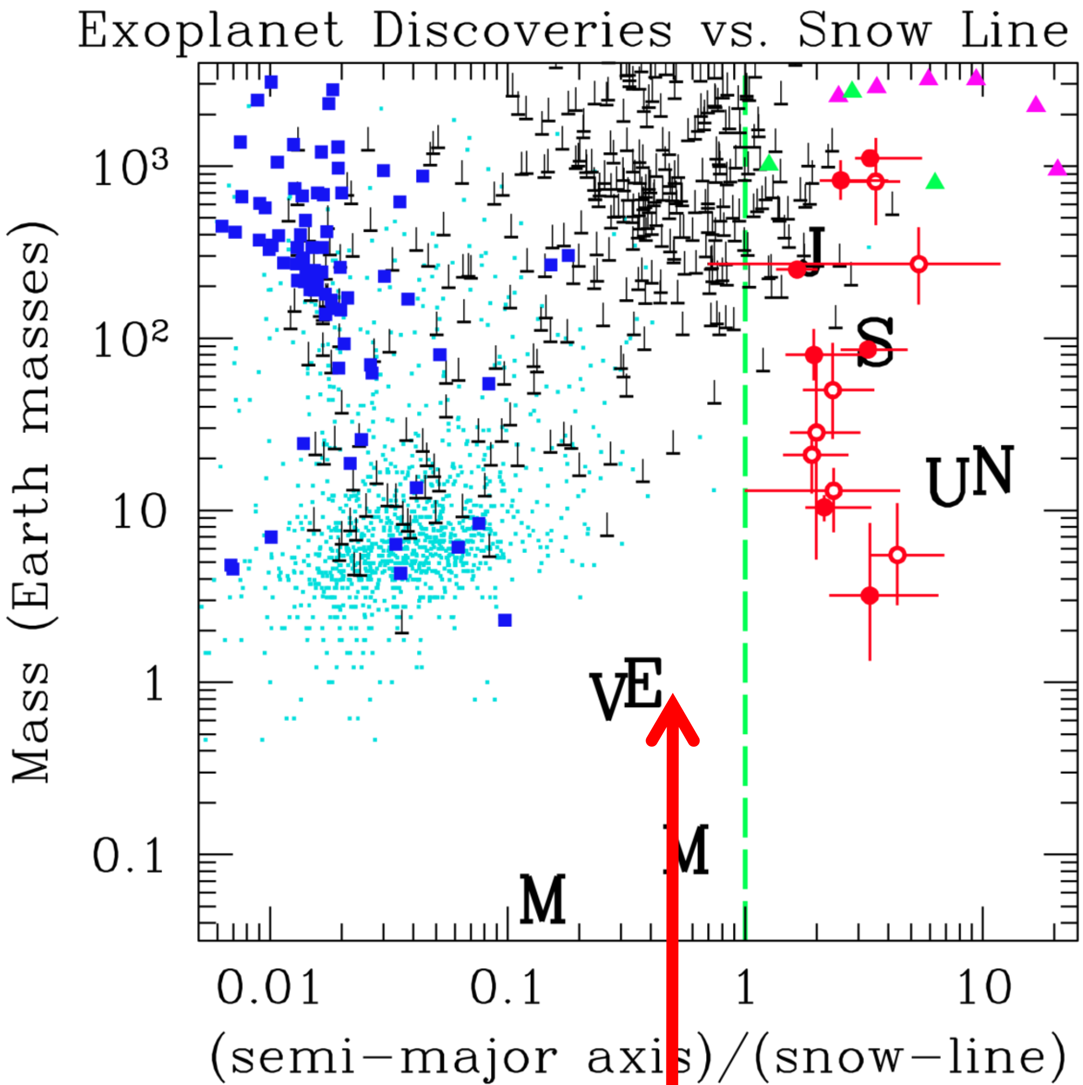
- ~400 Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
  - cool, low-mass planets
- Direct detection, and timing are magenta and green triangles
- Kepler candidates are cyan spots



Planet mass vs. semi-major axis/snow-line

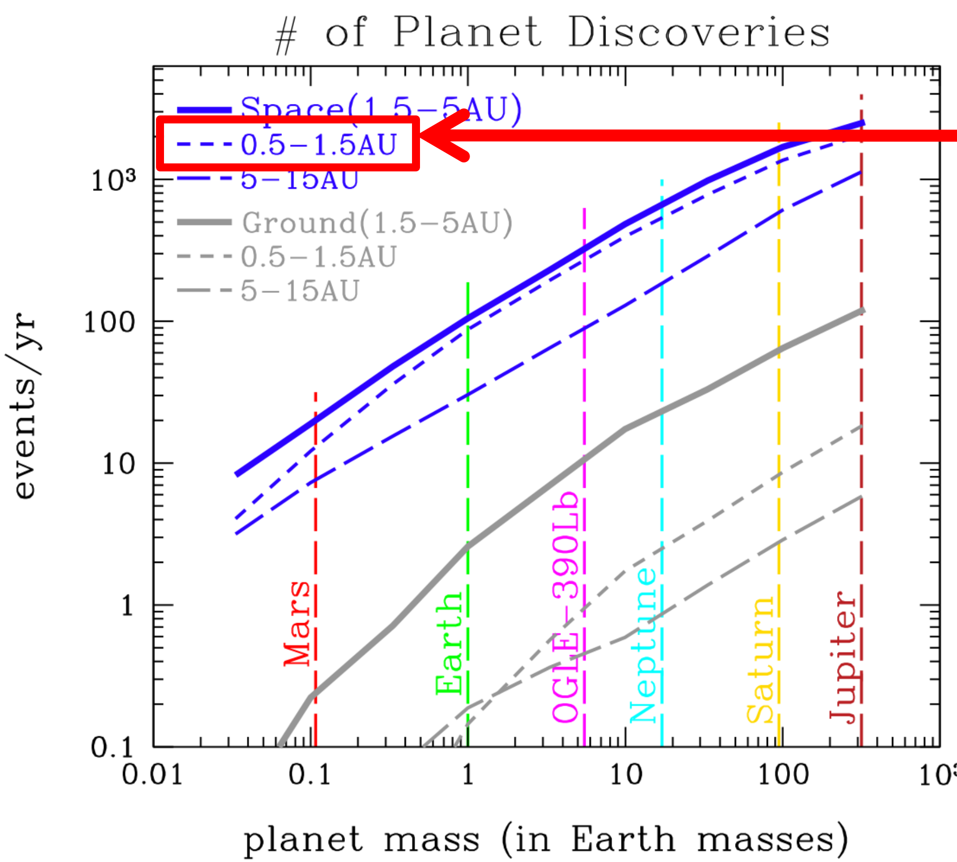
- "snow-line" defined to be 2.7 AU ($M/M_{\odot}$)
  - since $L \propto M^2$ during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles
- Kepler candidates are cyan spots

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered

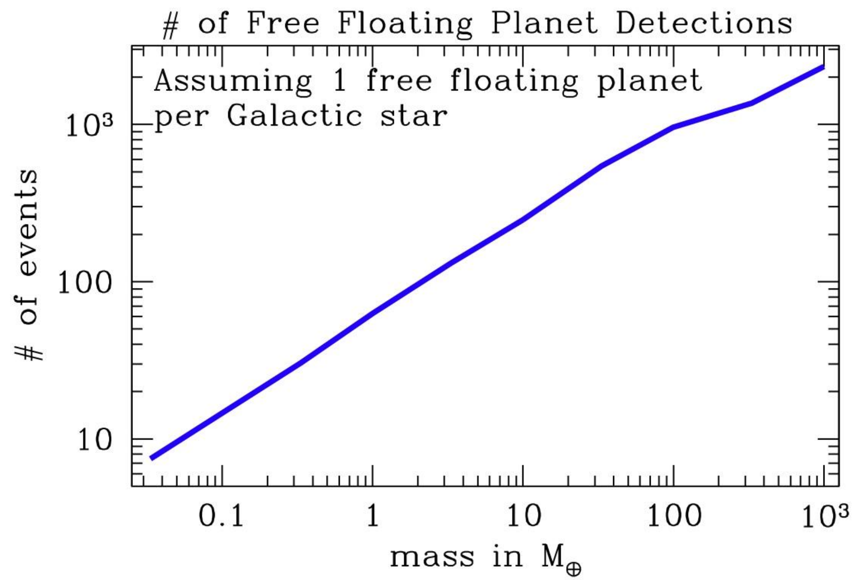


Fill gap between Kepler and ground ML

WFIRST's Predicted Discoveries



Pick a separation range that cannot be done from the ground; wider separation planets will also be detected.



The number of expected WFIRST planet discoveries per 9-months of observing as a function of planet mass.

WFIRST Top-Level Science Objectives

1. Complete the census of exoplanets from Earth-like planets in the habitable zone to free-floating planets.
2. Determine the expansion history of the Universe and its growth of structure so as to test explanations of its acceleration such as Dark Energy and modifications to Einstein's gravity.
3. Serendipitously survey the NIR sky at wavelengths that detect the bulk of the star formation history of the Universe.

WFIRST Microlensing Figure of Merit

- FOM1 - # of planets detected for a particular mass and separation range
  - Cannot be calculated analytically – must be simulated
    - Analytic models of the galaxy (particularly the dust distribution) are insufficient
  - Should not encompass a large range of detection sensitivities.
  - Should be focused on the region of interest and novel capabilities.
  - Should be easily understood and interpreted by non-microlensing experts
    - (an obscure FOM understood only be experts may be ok for the DE programs, but there are too few microlensing experts)
- FOM2 – habitable planets - sensitive to Galactic model parameters
- FOM3 – free-floating planets – probably guaranteed by FOM1
- FOM4 – number of planets with measured masses
    - Current calculations are too crude

Figure of Merit

$$\boxed{FOM \equiv (N_{\oplus} N_{HZ} N_{ff} N_{20\%})^{1/8} \propto T^{1/2}}$$

1. $N_{\oplus}$: Number of planets detected (at $\Delta\chi^2$=160) with a M=$M_{\oplus}$ and P = 2 yr, assuming every MS star has one such planet.
   - Region of parameter space difficult to access from the ground.
   - Uses period rather than semimajor axis as P/R_E is a weaker function of primary mass than a/R_E.
   - Designed to be diagnostic of the science yield for the experiment. If mission can detect these planets, guaranteed to detect more distant planets
2. N_{HZ}: Number of habitable planets detected assuming every MS star has one, where habitable means 0.5-10M_{Earth}, and [0.72-2.0 AU]$(L/L_{sun})^{1/2}$
3. N_{ff}: The number of free-floating 1M_{Earth} planets detected, assuming one free floating planet per star.
4. $N_{20\%}$: The number of planets detected with a M=M_{Earth} and P=2 yr for which the primary mass can be determined to 20%.

ExoPAG input on N_{HZ} or $\eta_{\oplus}$?

- Kepler measures $\eta_{\oplus}$, so WFIRST value is somewhat redundant
  - but $\eta_{\oplus}$ is important, so redundancy is good, although not critical
  - false alarm probabilities are smaller for microlensing than for transits, but IR imaging of important Kepler transits can probably keep the false alarm rate low for Earths near the HZ
- Kepler is not so good at finding planets in the outer edge of the HZ
  - Outer HZ planets might be easier to find with some direct detection mission designs
  - Should WFIRST focus on measurements in the outer HZ?

FOM Priors

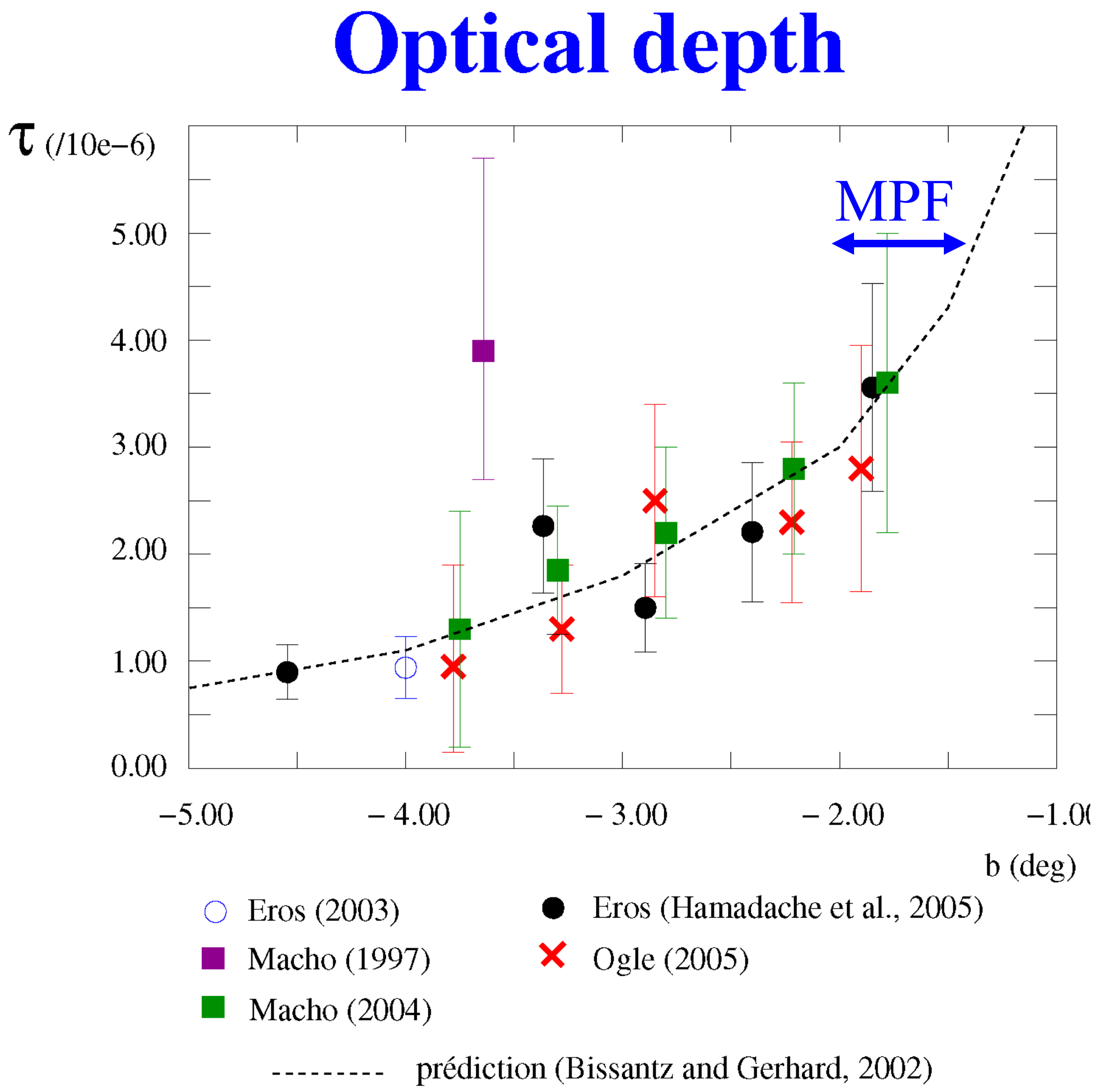
- Stage 1 = now
- Stage 2 = at launch
- Stage 1 priors all ~0
- Stage 2 priors mostly ~0 or << WFIRST
  - FOM-2 N_{HZ} value from Kepler will depend on mission extension and assumed optimism about final results
  - From Wes vs. Mike and Joe
    - we can conclude that log $\eta_{\oplus} = -1 \pm 2$

Mission Simulation Inputs

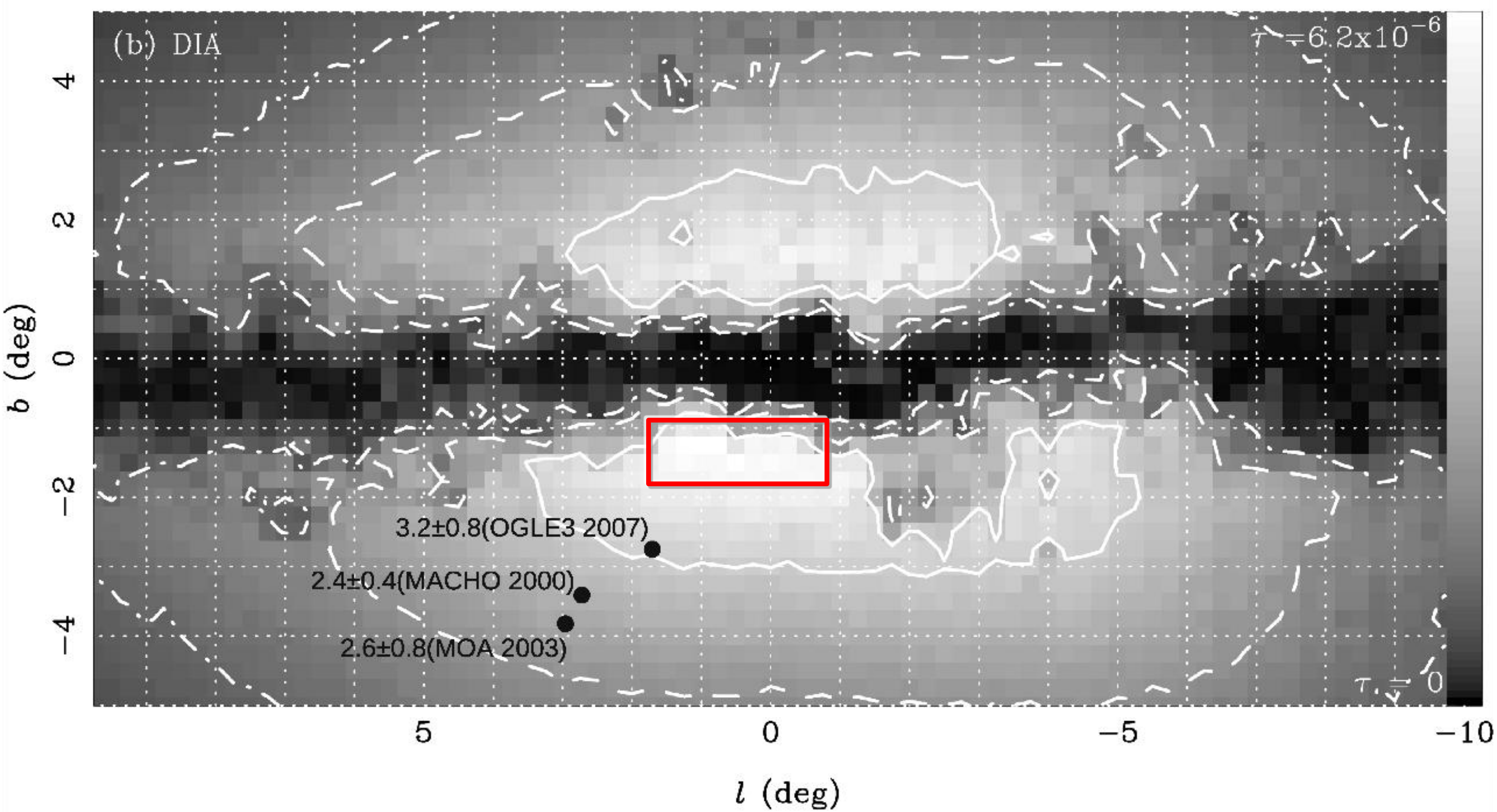
- Galactic Model
  - foreground extinction as a function of galactic position
  - star density as a function of position
  - Stellar microlensing rate as a function of position
- Telescope effective area and optical PSF
- Pixel Scale – contributes to PSF
- Main Observing Passband ~ 1.0-2.0 μm
  - throughput
  - PSF width
- Observing strategy
  - # of fields
  - Observing cadence
  - Field locations

Microlensing Optical Depth & Rate

- Bissantz & Gerhard (2002) τ value that fits the EROS, MACHO & OGLE clump giant measurements
- Revised OGLE value is ~20% larger than shown in the plot.
- Observations are ~5 years old



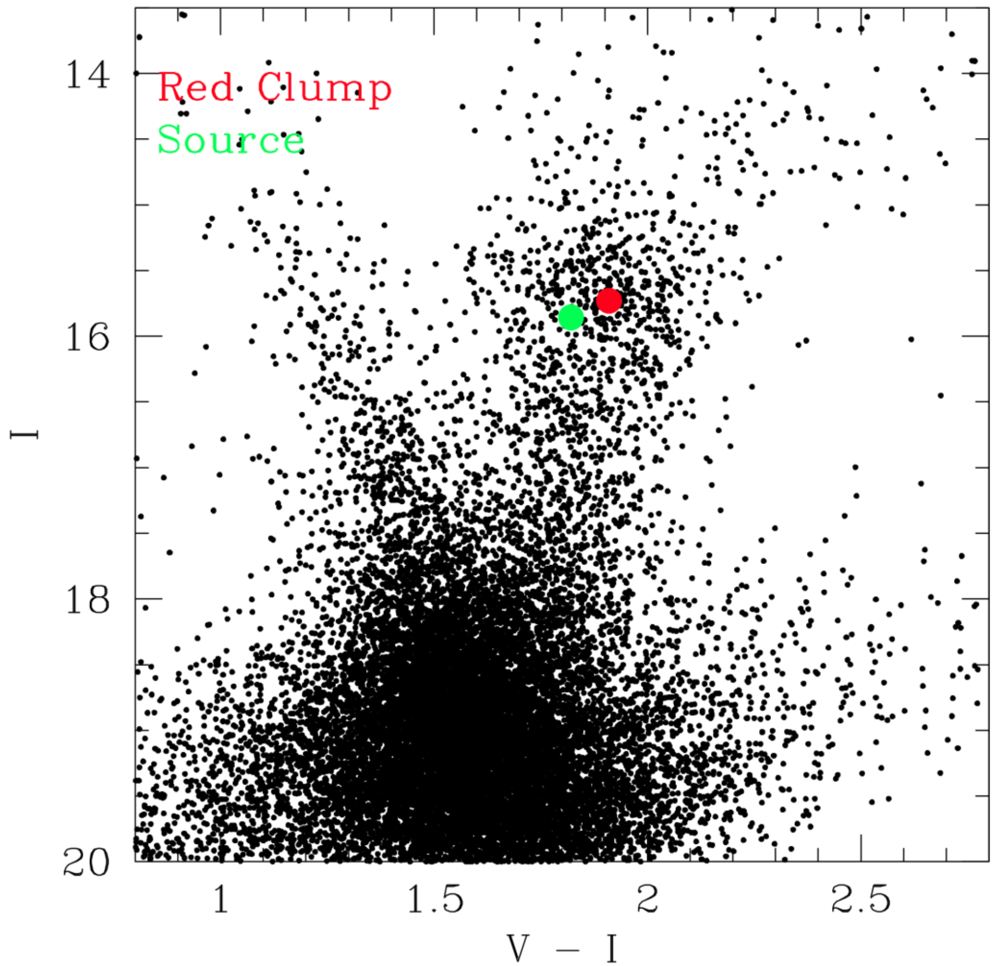
Select Fields from Microlensing Rate Map
(including extinction)



Optical Depth map from Kerins et al. (2009)   - select more fields than needed

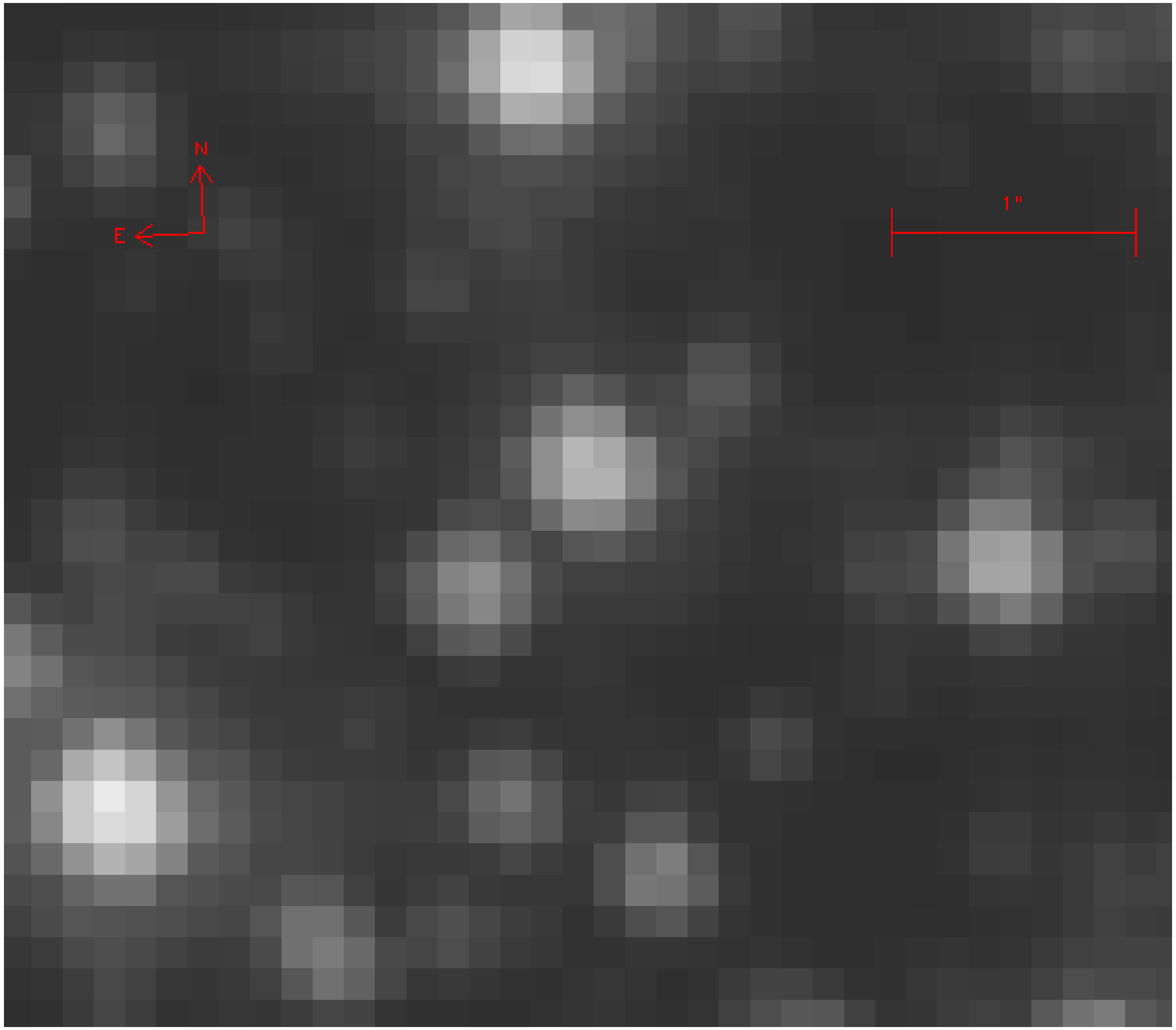
Determine Star Density

- Match Red Clump Giant Counts for selected fields
- Varies across the selected fields
- Use HST CM diagram for source star density



Create Synthetic Images & Simulate Observing Program

- Simulate photometric noise due to blended images
- Depends on
  - Star density
  - Pixel scale
  - Passband
  - Telescope design
- Simulate Microlensing light curves
  - Depends on observing cadence
- Identify simulated light curves with detectable planetary signals
- Determine planet detection rate



Parameter Uncertainties

- Send simulated light curve data to Scott Gaudi (and Joe Catanzarite from JPL-WFIRST Project Office)
- They estimate parameter uncertainties using a Fisher-Matrix method
- Evaluate planet discovery penalties from interruptions of observations

Future Work (2nd SDT Report)

- Use lens star detection and/or microlensing parallax to determine host star masses
- Add this to Fisher matrix parameter uncertainty estimates

mass-distance relations:

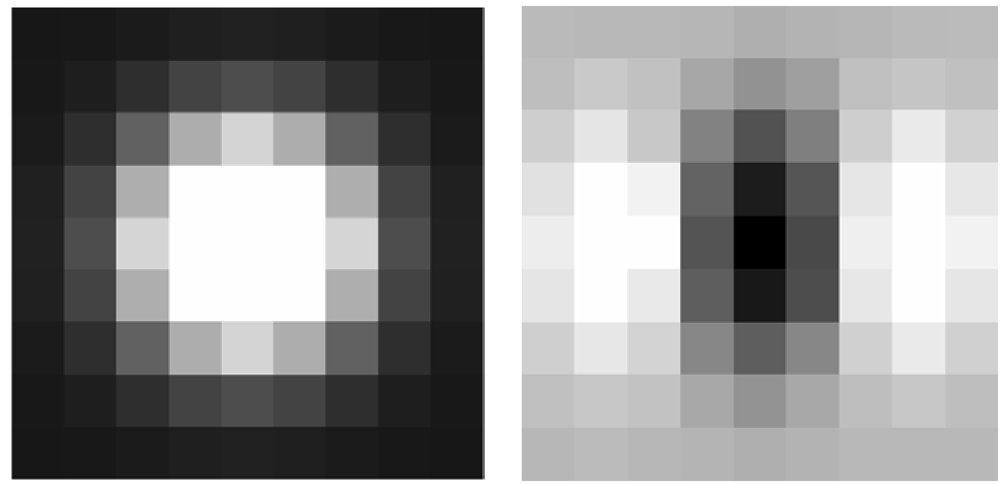
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

Simulate Lens Star Detection in **WFIRST** Images

Denser fields yield a higher lensing rate, but increase the possibility of confusion in lens star identification.

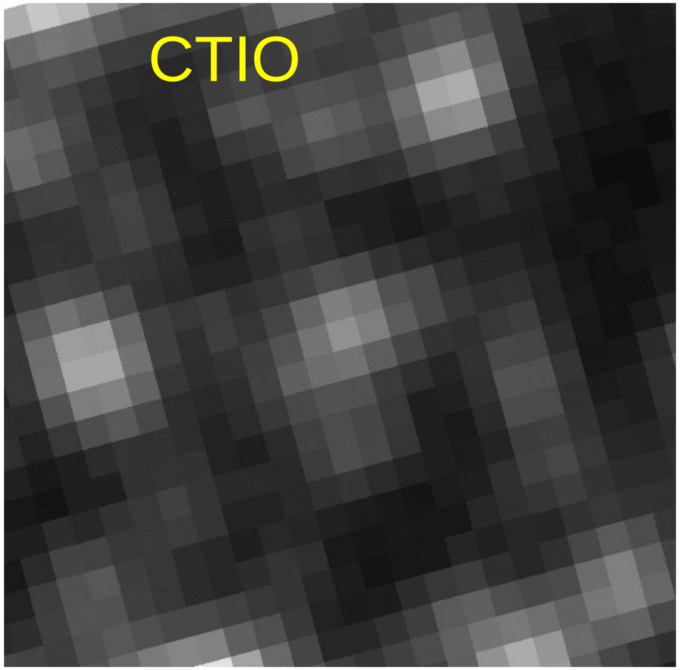


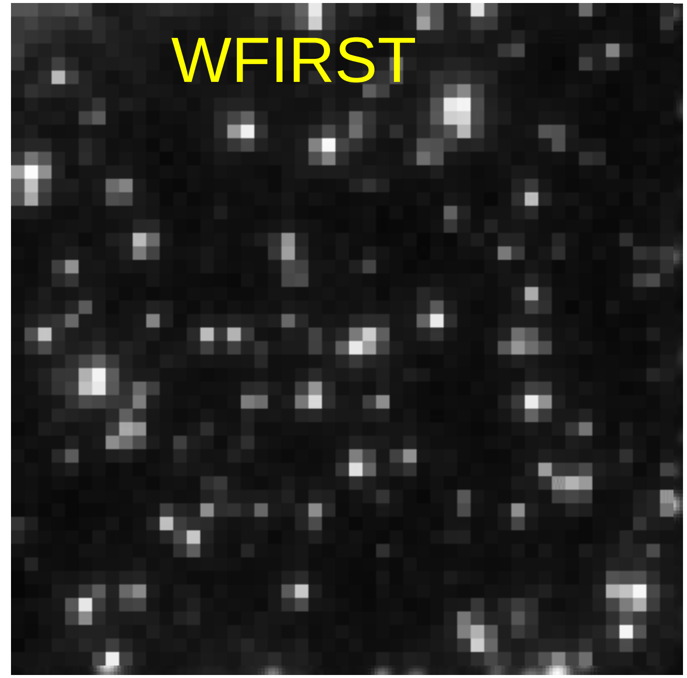
A 3× super-sampled, drizzled 4-month MPF image stack showing a lens-source blend with a separation of 0.07 pixel, is very similar to a point source (left). But with PSF subtraction, the image elongation becomes clear, indicating measurable relative proper motion.

Why Space-based Microlensing?

- Microlensing requires extremely crowded fields
- Source stars only resolvable from space
- Ground-based surveys need high lensing magnification to resolve most source stars
  - Limits sensitivity to near the Einstein ring
  - Space-based microlensing sensitive from 0.5 AU - ∞
- Space-based microlensing allows detection of most lens stars
  - Allows direct determination of star and planet masses
- Simulations from Bennett & Rhie (2002)
- Basic results confirmed by independent simulations (Gaudi)
- MPF Discovery proposal (2006) -> WFIRST

Ground-based confusion, space-based resolution





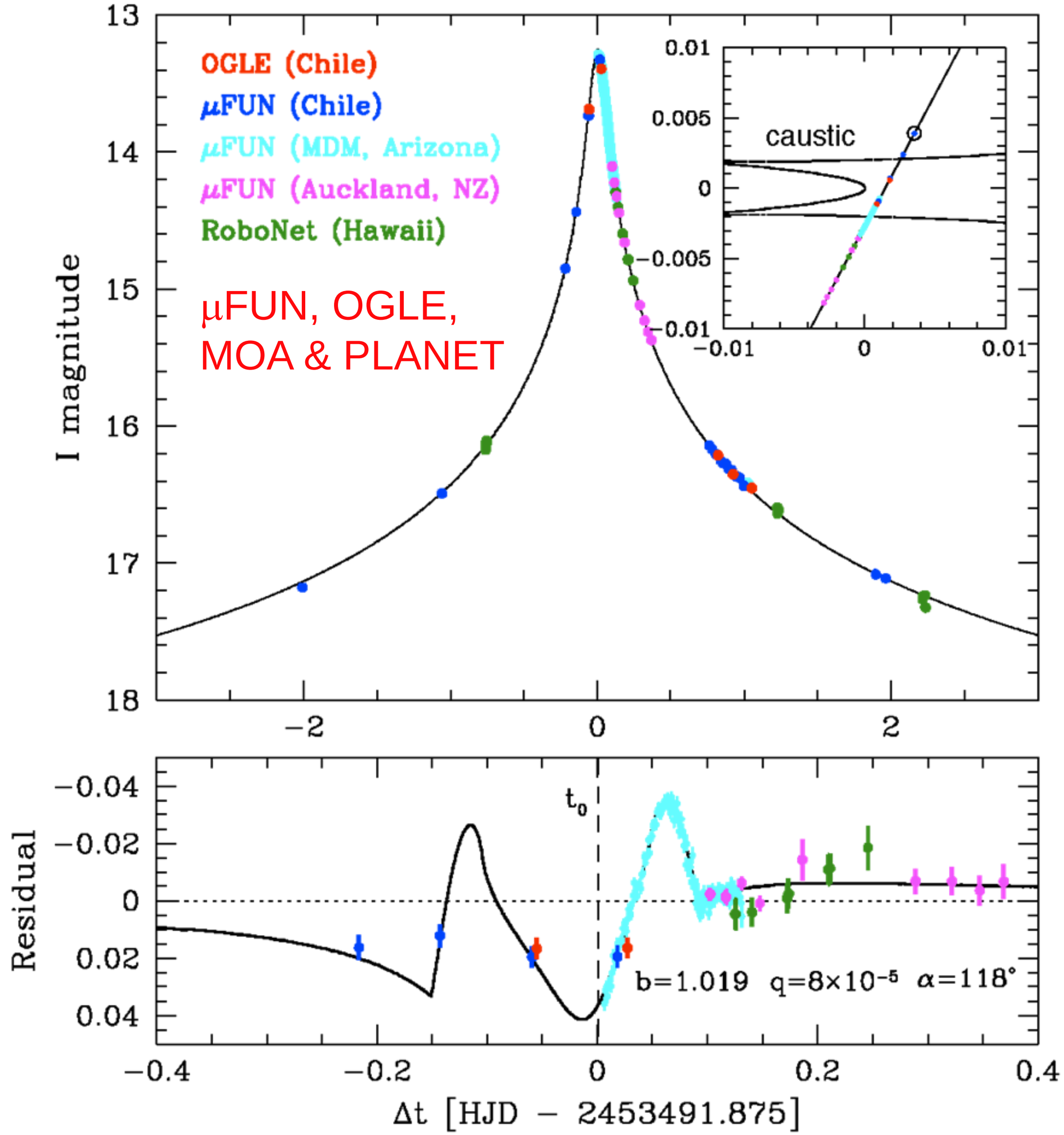
- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Microlensing Planet Finder (MPF)
- Space observations needed for sensitivity at a range of separations and mass determinations

High-magnification: Low-mass planets

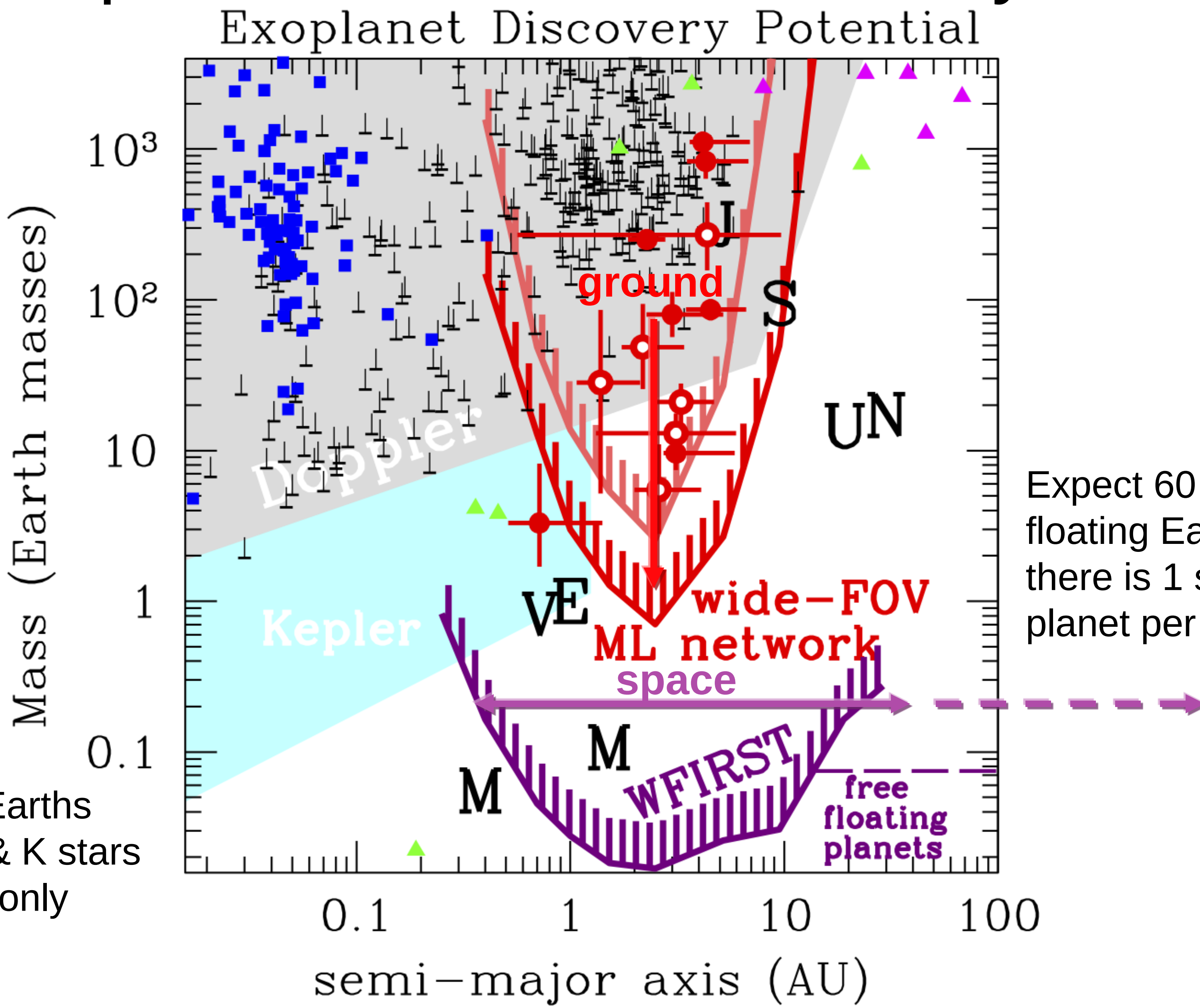
OGLE-2005-BLG-169Lb

- Detection of a ~13 $M_\oplus$ planet in a A_{max}= 800 event
- Caustic crossing signal is obvious when light curve is divided by a single lens curve.
- Detection efficiency for ~10 $M_\oplus$ planets is << than for Jupiter-mass planets

- Competing models with an Earth-mass planet had a signal of similar amplitude
- So, an Earth-mass planet could have been detected in this event!



Space vs. Ground Sensitivity



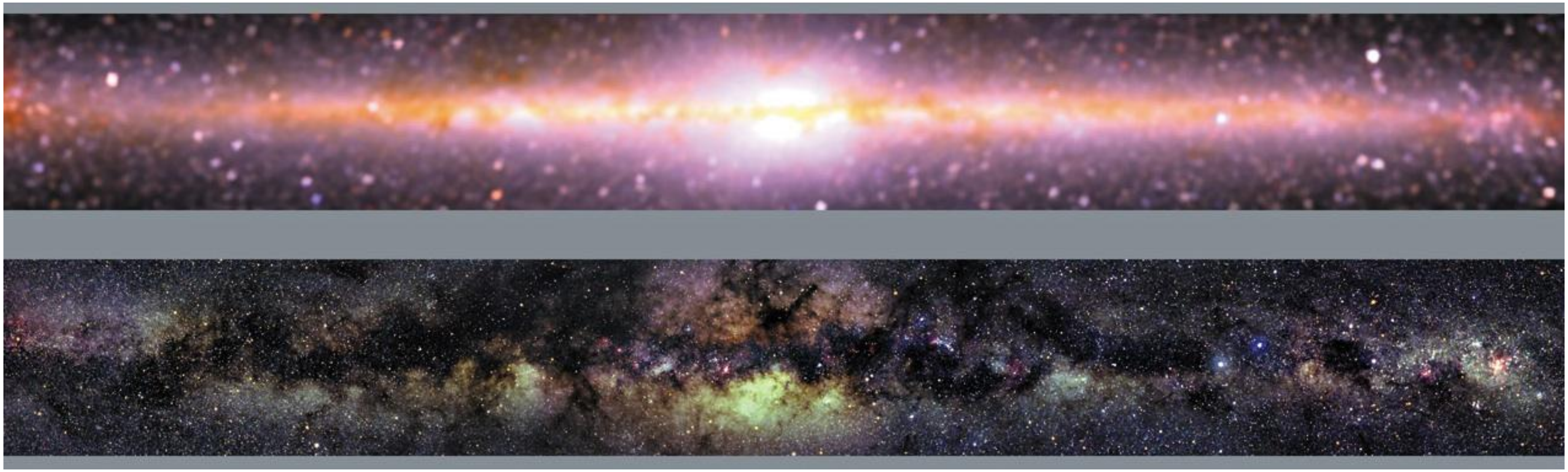
Expect 60 free-floating Earths if there is 1 such planet per star

Habitable Earths orbiting G & K stars accessible only from space

Infrared Observations Are Best

The central Milky Way:

near infrared



optical

Dust obscures the best microlensing fields toward the center of the Galaxy

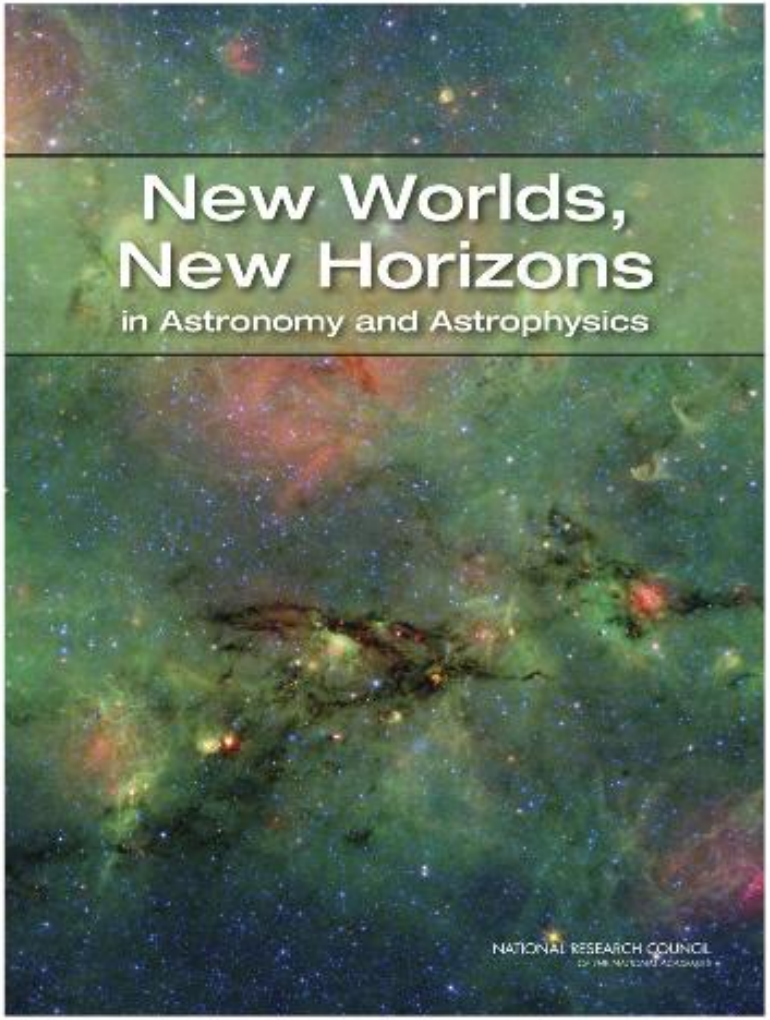
Astro-2010 Decadal Survey

"**WFIRST** designed to settle important questions in both exoplanet and dark energy research"

"the Kepler satellite … should be capable of detecting Earth-size planets out to almost Earth-like orbits."

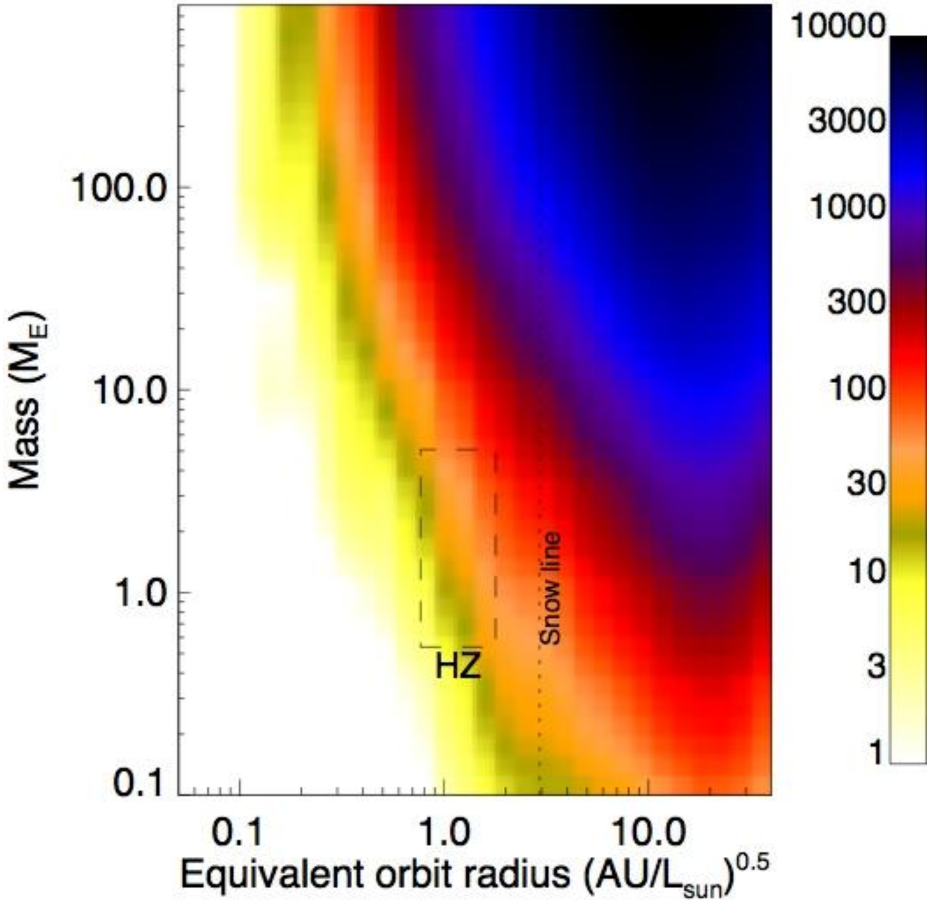
"As microlensing is sensitive to planets of all masses having orbits larger than about half of Earth's, WFIRST would be able to complement and complete the statistical task underway with Kepler, resulting in an unbiased survey of the properties of distant planetary systems.

WFIRST does a microlensing planet search, multiple dark energy studies plus IR surveys and GO observations

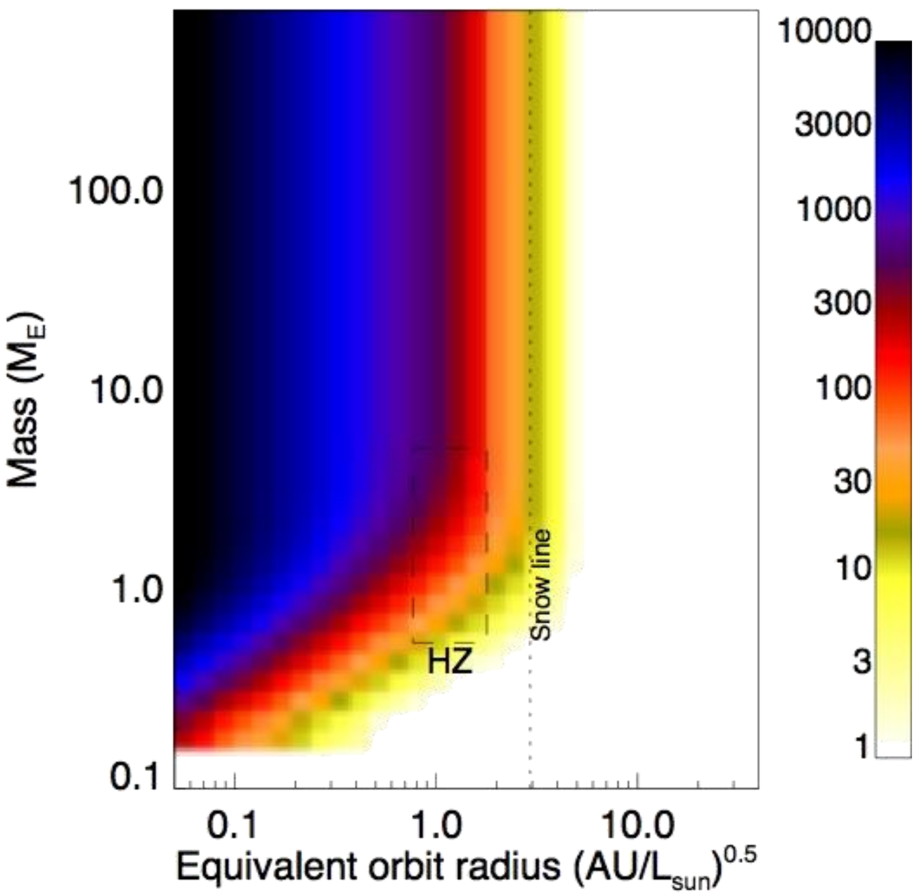


WFIRST vs. Kepler

WFIRST – w/ extended mission

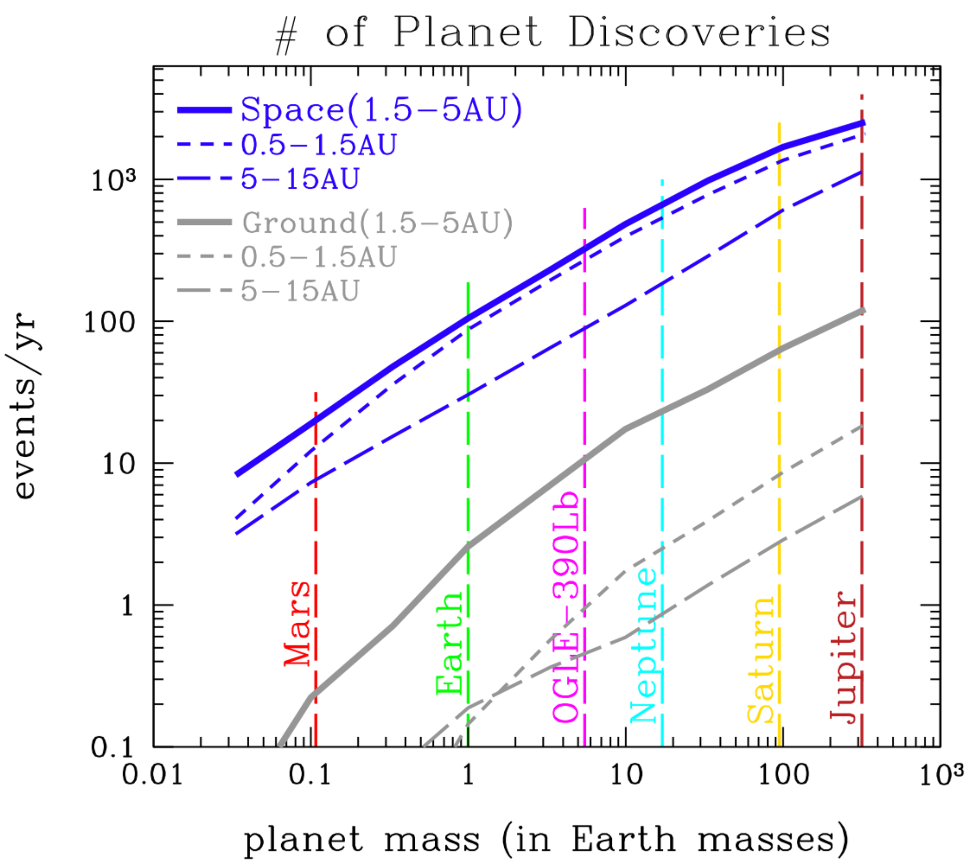


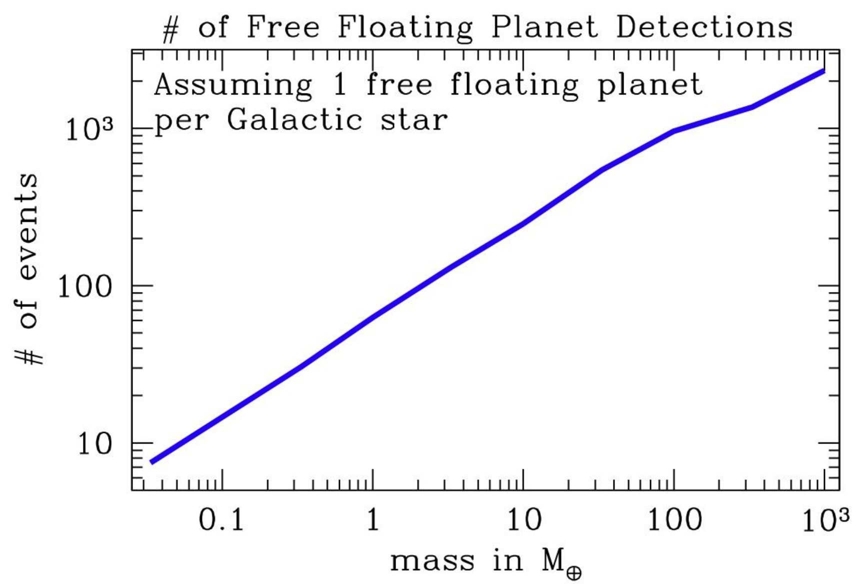
Kepler 6yr



Figures from B. MacIntosh of the ExoPlanet Task Force

WFIRST's Predicted Discoveries

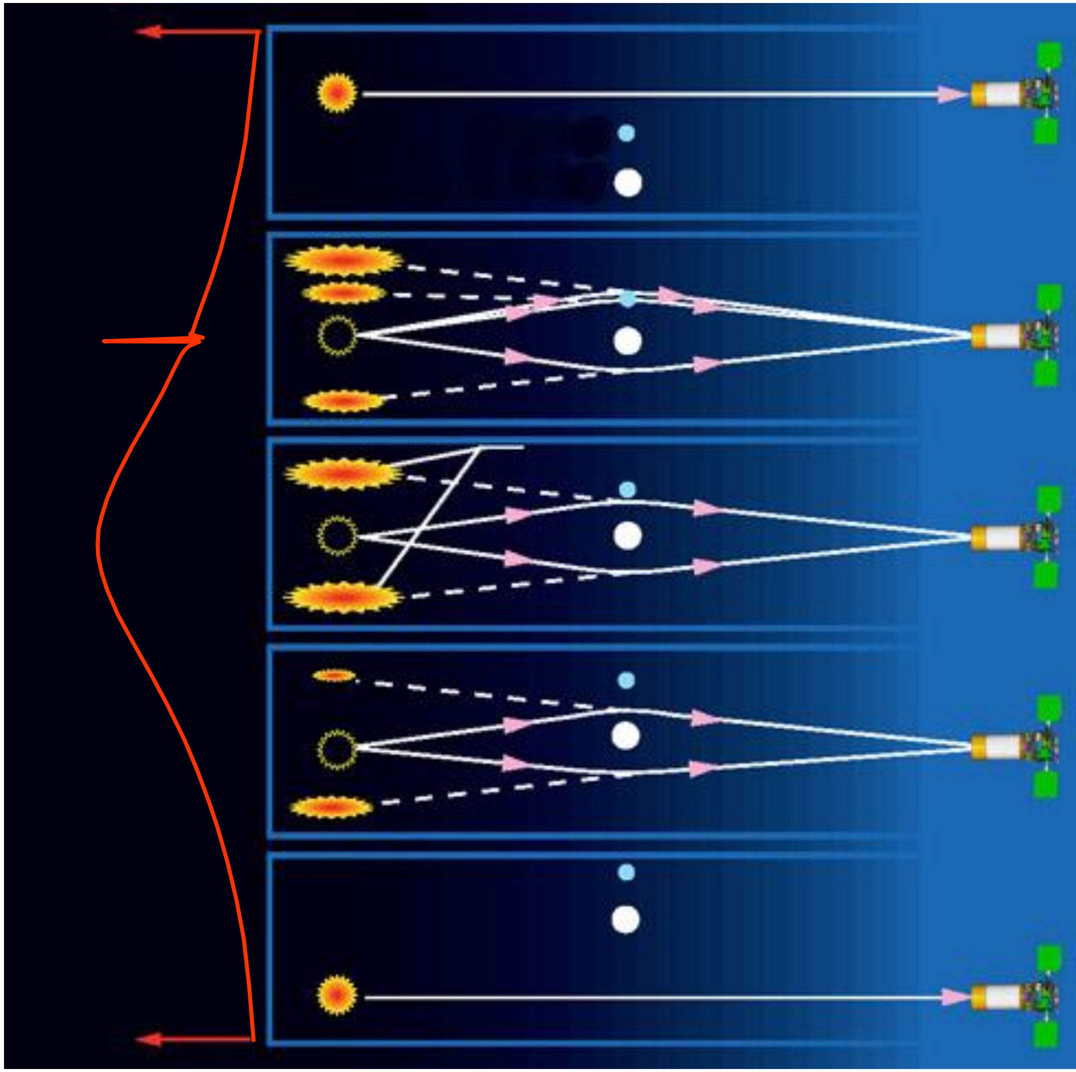




The number of expected WFIRST planet discoveries per 8-month observing season as a function of planet mass.

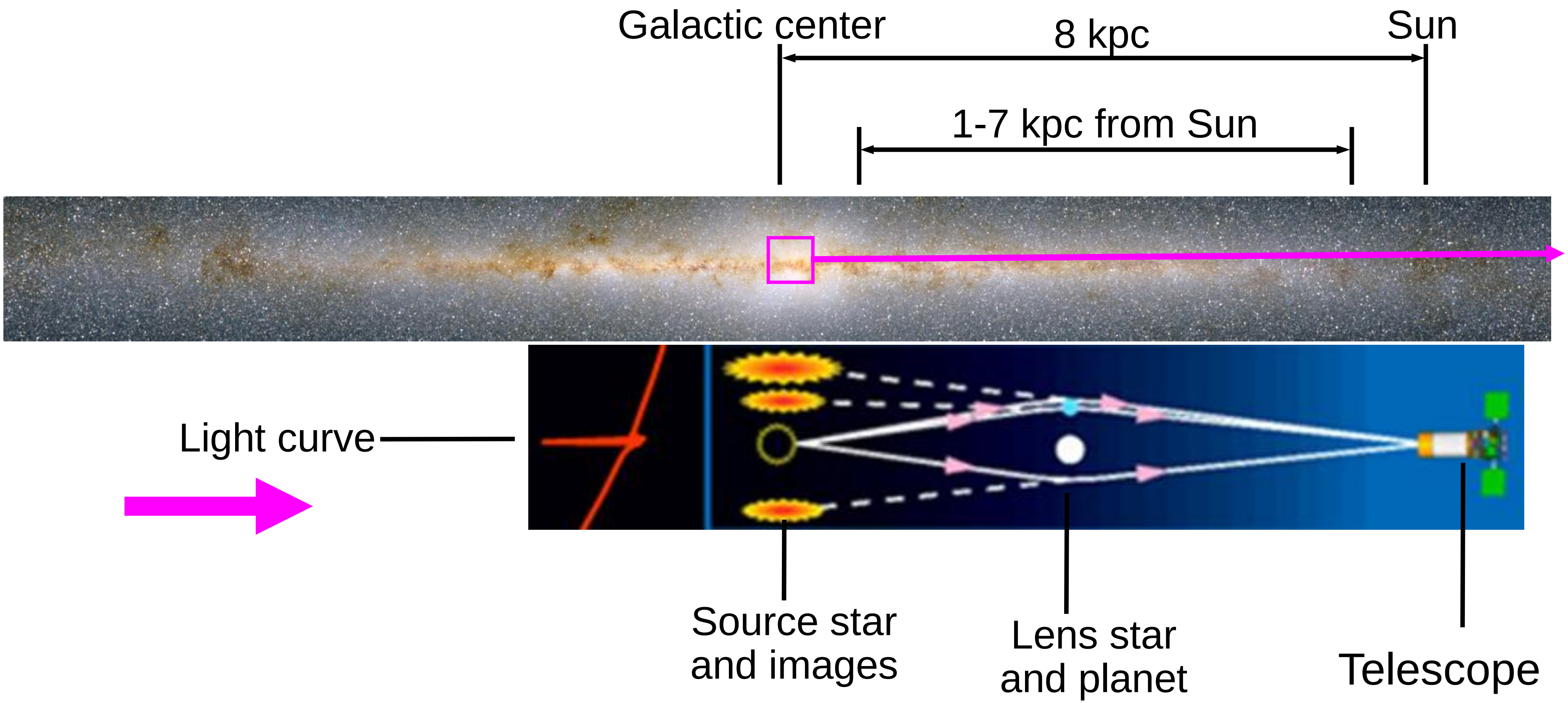
The Physics of Microlensing

- Foreground “lens” star + planet bend light of “source” star
- Multiple distorted images
  - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E



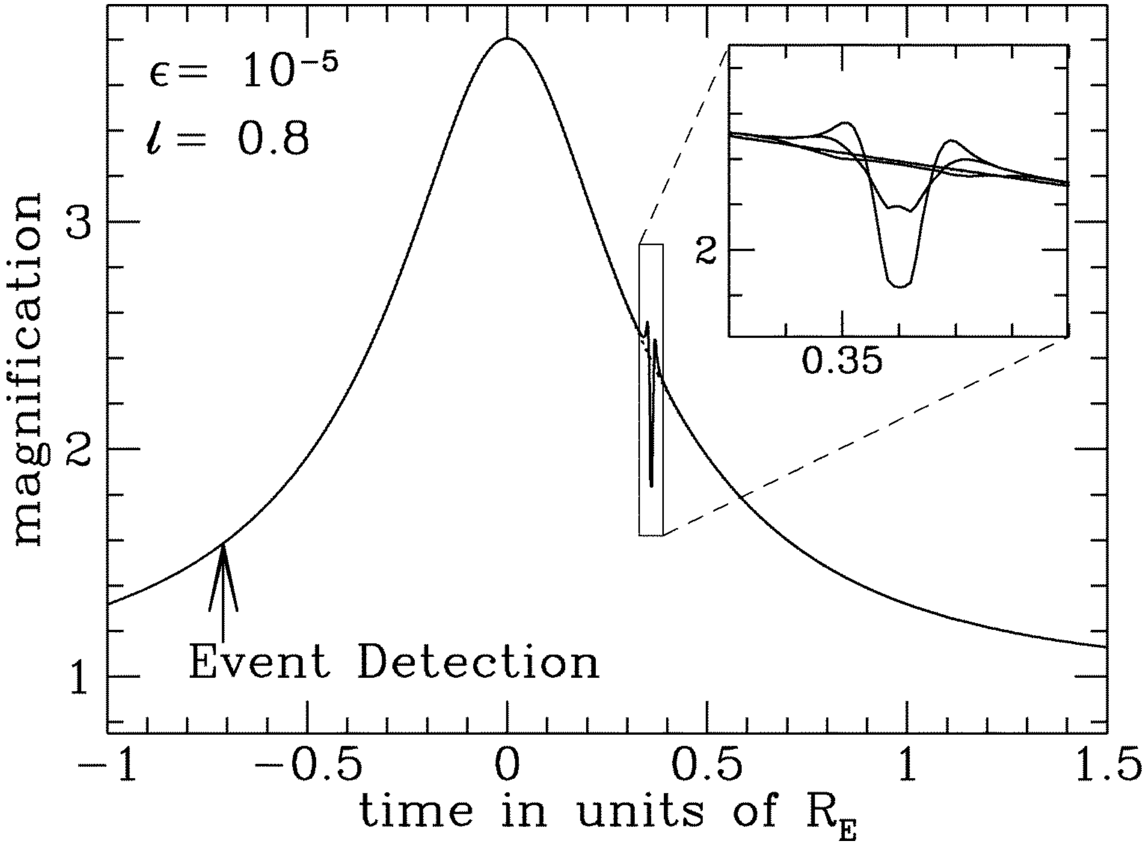
$$\text{Key Fact: } 1\ \text{AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\frac{2GM}{c^2} R_{GC}}$$

Microlensing Target Fields are in the Galactic Bulge



10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

How Low Can We Go?



(Bennett & Rhie 1996)

Limited by Source Size

angular Einstein radius

$$\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\odot}\right)^{1/2}$$

$\updownarrow$

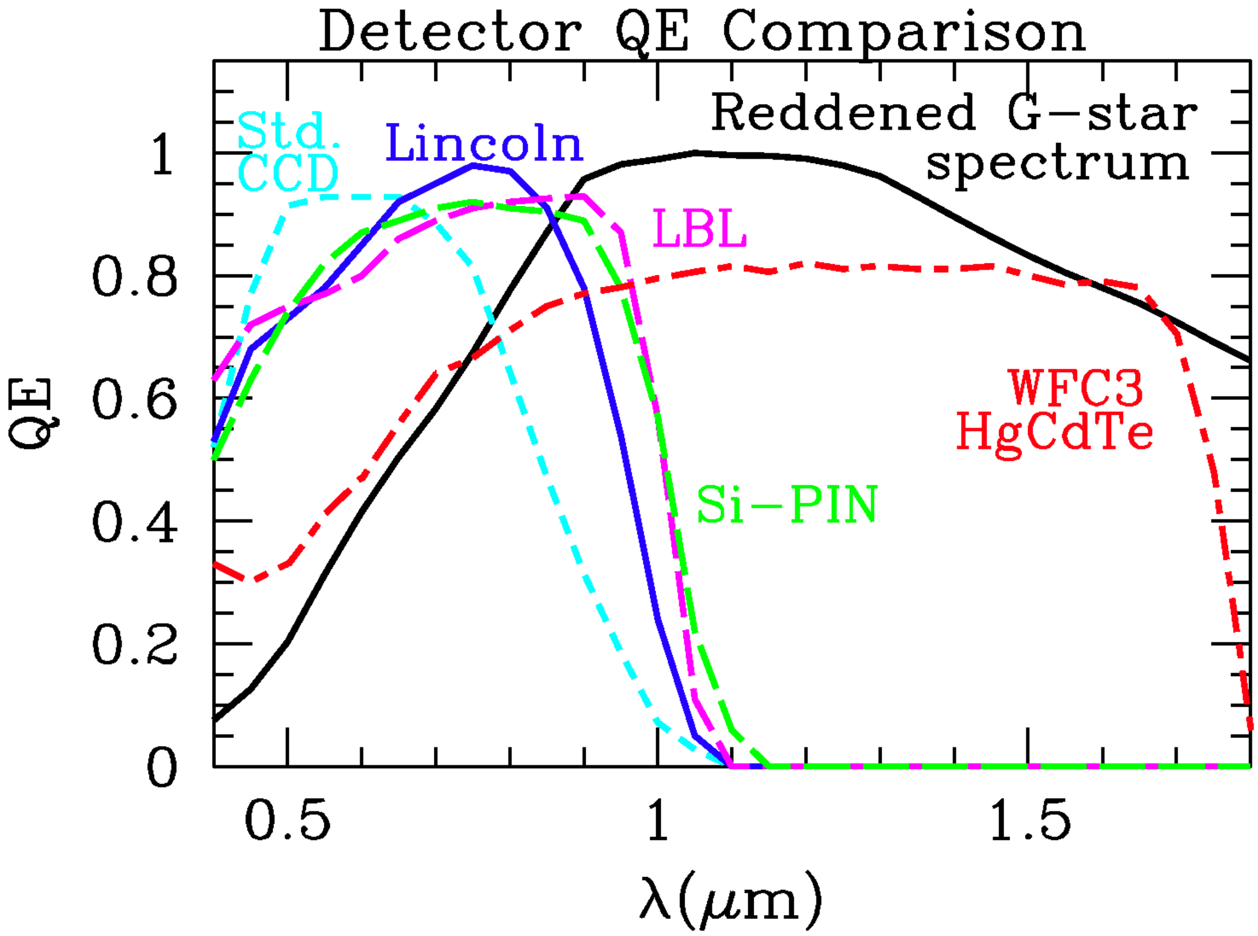
$$\theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)$$

angular source star radius

For $\theta_E \geq \theta_*$:
low-mass planet signals are rare and brief, but not weak

Mars-mass planets detectable
if solar-type sources can be monitored!

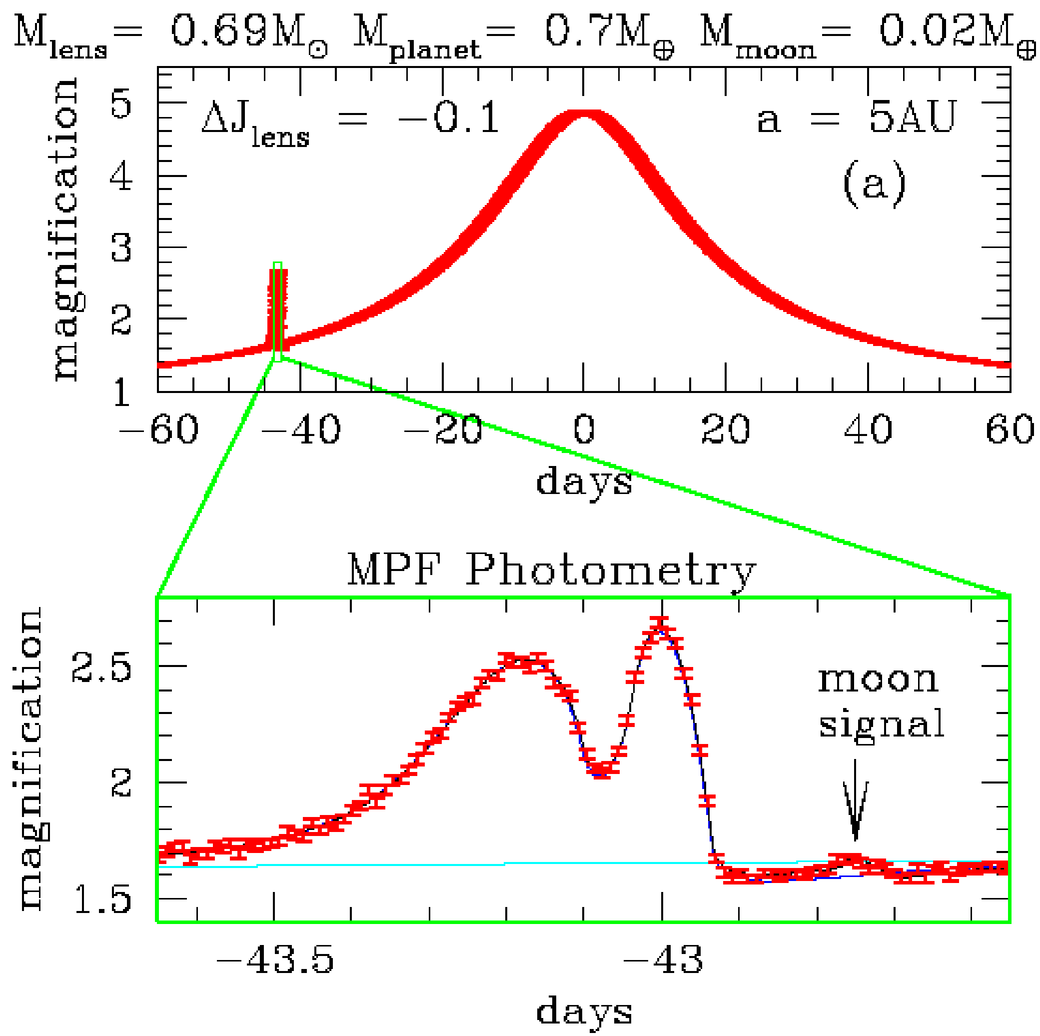
Detector Sensitivity



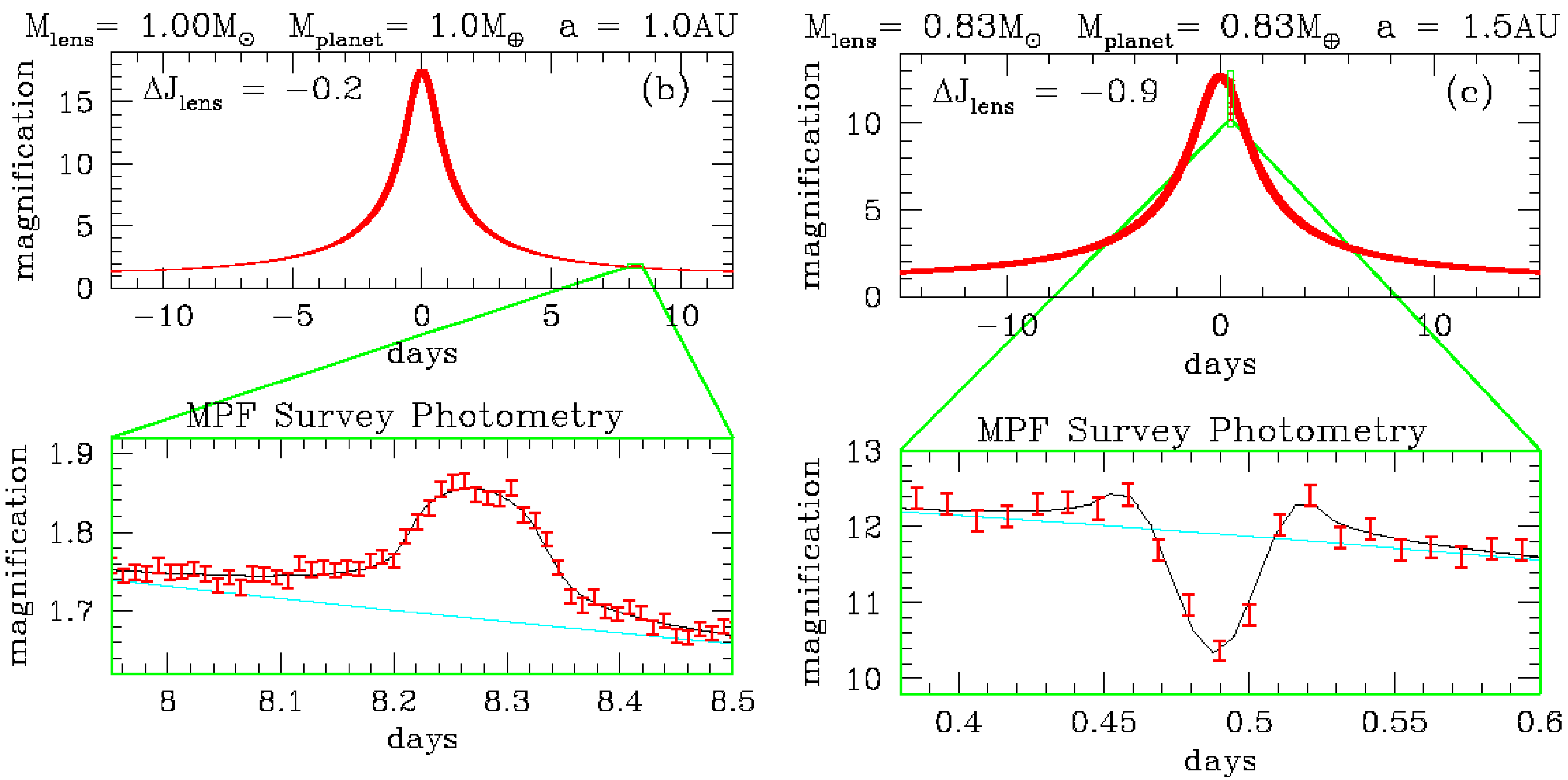
The spectrum of a typical reddened source star is compared to the QE curves of CCDs and Si-PIN detector arrays. The HgCdTe detectors developed for HST’s WFC3 instrument can detect twice as many photons as the most IR sensitive Si detectors (CCDs or CMOS). MPF will employ 35 HgCdTe detectors. 3 filters: “clear” 600-1700nm, “visible” 600-900nm, and “IR” 1300-1700nm.

Simulated Planetary Light Curves

- Planetary signals can be very strong
- There are a variety of light curve features to indicate the planetary mass ratio and separation
- Exposures every 10-15 minutes
- The small deviation at day –42.75 is due to a moon of 1.6 lunar masses.



Simulated MPF Light Curves



The light curves of simulated planetary microlensing events with predicted MPF error bars. ΔJ_{lens} refers to the difference between the lens and source star magnitudes. The lens star is brighter for each of these events.